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Oil removing efficiency in oil–water separation flotation column

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ABSTRACT

An oil–water separation flotation column with a unique structure was used in oil–water separation fields. The oil–water separation flotation column contains the cyclonic separation and airflotation separation with advantages in the oily sewage treatment field such as low effective separation size, short separation time, large handling capacity, and low operating cost, especially in polymer-flooding-drive oily sewage treatment aspect. In this paper, the oil removal efficiencies of the cyclonic and airflotation sections of the oil–water separation flotation column were investigated. In addition, several operating parameters which impact separation such as feeding speed, aeration rate, circulating pressure, underflow split ratio, frother consumption were also investigated. The optimum operating parameters determined for the oil–water separation flotation column were a feeding speed of $1.50\,m^3\,h^{-1}$, an aeration rate of $2.50\,m^3\,h^{-1}$, and a circulating pressure of 0.28 MPa. A bottom flow diversion ratio of 95% and final effluent oil content of $16.49\,mg\,L^{-1}$ were also determined. Furthermore, three separation models for the cyclonic section separation, the airflotation section separation and the whole column separation were constructed.

Keywords: Oil–water separation flotation column; Airflotation section; Cyclonic section; Oil removing efficiency

1. Introduction

Currently, many domestic oilfields are in the medium, high, and extra-high water cut stage of the mid-to-late petroleum exploitation period, the polymer flooding and the ternary complex flooding have been widely applied in the oilfield [1–3]. Thus, the oily sewage treatment has become one key issue for the production process of the oilfield industry and environment protection [4–6]. In recent years, the technology of cyclonic separation and airflotation are extensively applied to the oilfield ground engineering [7], but the oily sewage treatment effect is unsatisfied if either the technology of cyclonic separation or airflotation is used separately [8–10]. An oil–water separation flotation column with a unique structure has been introduced to the oil–water separation field [11] and has great advantage in oil–water separation because of the synergistic effect between the cyclonic separation and airflotation [12].

The oil–water separation flotation column is a complicated separation process comprising of both commonly used cyclonic and airflotation separations.

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The oil–water separation efficiency of flotation column consists of the cyclonic separation section and airflotation section, which are significant to further improve the oil–water separation efficiency of the oil–water separation flotation column [13–15].

2. Oil–water separation process of the flotation column

The oil–water separation flotation column is a combination of the floatation column and the common static hydraulic cyclone. It is mainly includes a cylinder, a circulating pump, a bubble generator, and a sieve plate. The 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 are collected by foam tank and then discharged. Droplets with good floatability droplets are effectively separated through the stage of column flotation. The poor floatability droplets get into the bottom of the column prior to cyclone separation where they are pulled out by the circulating pump tangentially, 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 through sieve plate in flotation column. The effect of oil–water separation is improved. The emulsification oil droplets are transported from cyclone separation zone to airflotation separation zone by the oil–gas complex which formed by the carry role of microbubbles, the oil–water separation has finished [16]. The airflotation separation area has static separation effect of the "long and narrow" environment with "quiet" fluid dynamics.

The oil–water separation flotation column is integrated with the cyclonic and flotation separation technology [17]. In addition, the synergistic effect of multiple separation modes reinforces the separation effect and expands the size range of the oil content 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.

3. Experimental

3.1. Oily sewage sample

The water sample for the experiment was taken from the primary oil, gas, and water separation tank in the No. 6 United Station of Shengli Isolated Island Oilfield. The water quality analysis result of the oily sewage sample is presented in Table 1. It can be seen that the oily sewage quality of the No. 6 United Station of Shengli Isolated Island Oilfield was bad; the sample color was yellowish-brown, with lots of dispersed oil and suspended matter. Besides, due to the high oil content and high content of suspended matters and polymers, the emulsion in the oily sewage of the No. 6 United Station of Shengli Isolated Island Oilfield was stable, it was hard to dispose.

3.2. Experimental setup

The process of treating oily sewage is shown in Fig. 1. The experimental setup includes the flotation column separation system and measurement control system. The separation system consists of the cyclonic-static microbubble flotation column, feeding pump (for inflow and outflow), circulating pump, mixing tank (dosing and mixing), and other devices. The cyclonic-static microbubble flotation column examined in this experiment has a diameter of 400 mm, height of 4,000 mm, and is made of PMMA material. The control system for measurement is composed of the gas flowmeter, liquid flowmeter, electric control valve, pid digital regulator, and gas content determinator. The automatic control system for liquid surface of the flotation column is composed of the pressure transmitter, electronic control valve for straight travel, pid digital regulator.

Firstly, the oily sewage from the primary separation tank entered into the mixing drum, and its flow was regulated. Subsequently, the inflow was supplemented from the mid-upper part of the flotation column via the feeding pump. Finally, the outflow was drained from the flotation column bottom via the control valve. The aeration rate was measured and regulated by the gas flowmeter and the circulating pressure was regulated by adjustment of the circulating pump speed [18].

3.3. Methods

Each experimental condition was tested for 6 h except debugging time. Water samples were taken every half hour and combined into one sample.

Table 1
Water quality analysis result of the oily sewage in No. 6 United Station of Shengli Isolated Island Oilfield

Type	pH	Temperature/℃	Density/g cm^{-3}	Viscosity/ MPa s	Oil content/ mg L^{-1}	HPAM content/ mg L^{-1}	Suspended solid content/mg L^{-1}
Analysis result	7.0–7.4	35–39	910–960	1.5238	2,000–2,500	150–300	50–680

In the experiment, the oil removal efficiency was used to evaluate the oil–water separation efficiencies of the cyclonic and airflotation sections in the oil–water separation flotation column. Sampling was taken from the sampling point 1 of the oily sewage inlet, the sampling point 2 of the tangential feeding port, and the sampling point 3 of the purified underflow outlet (Fig. 1), and the oil concentration at these three points are C_1, C_2, and C_3, respectively.

The cyclonic separation efficiency of the cyclonic section R_1 is:

$$R_1 = 1 - \frac{C_3}{C_2} \quad (1)$$

The airflotation separation efficiency of the airflotation section R_2 is:

$$R_2 = 1 - \frac{C_2}{C_1} \quad (2)$$

The whole column efficiency of the whole column R is:

$$R = 1 - \frac{C_3}{C_1} \quad (3)$$

The parameters that influence the cyclonic and airflotation separation efficiencies are the feeding speed g_l, circulating pressure p (circulation volume q_c), aeration rate q_g, and underflow split ratio f. The feeding speed was controlled by the flowmeter. The circulating pressure refers to the pressure at the circulating pump outlet of the flotation column. By controlling the pressure size, the tangential feeding flow can provided different energies to the cyclonic separation. In the experiment, the frequency converter (0–50 Hz) was used to change the circulating pump flow and regulate its outlet pressure. The aeration rate refers to the amount of gas sucked into the flotation column via the bubble generator, which can be measured and regulated via the gas flowmeter.

After being separated in the flotation column, one part of oily foam in the oily sewage was drained out via the overflow outlet, and remaining part was drained out via the underflow outlet. The flow is expressed by q_1 and q_2. Furthermore, the split ratio is used to describe relations between the overflow outlet flow q_1 and underflow outlet flow q_2, the ratio between the oil removal equipment and underflow outlet flow and the total feeding amount is called the underflow split ratio, that is:

$$f = \frac{q_2}{(q_1 + q_2)} \quad (4)$$

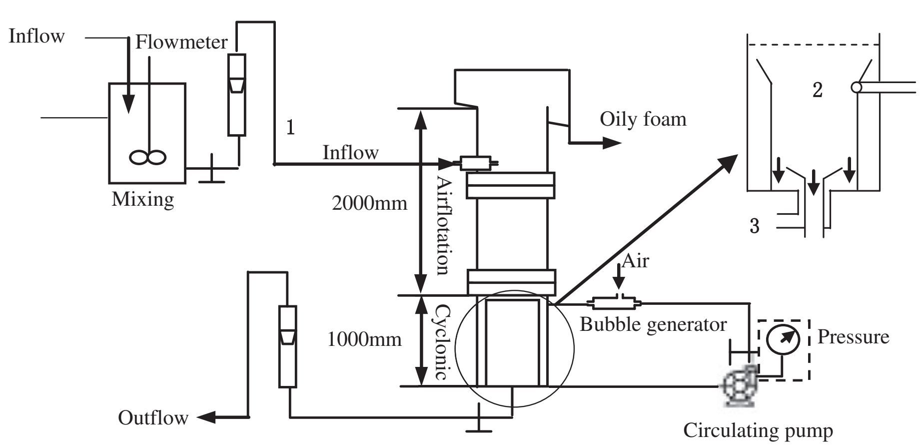

Fig. 1. Process of treating oily sewage by using oil–water separation flotation column.

4. Results and discussion

4.1. Effect of the feeding speed

Experiment conditions: $p = 0.26\,\text{MPa}$, $q_c = 20\,\text{m}^3\,\text{h}^{-1}$, $q_g = 3.0\,\text{m}^3\,\text{h}^{-1}$, and $f = 95\%$. The influence of feeding speed on the oil concentration of water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column is shown in Fig. 2.

As shown in Fig. 2, with increasing feeding speed, the oil removal rate reduced and the oil removal efficiency showed a decreasing trend. On the basis of the slope of three curves on oil removal efficiency, the feeding speed had more influence on the cyclonic section than others.

With the increasing of feeding speed, the collision probability between the oil droplets and bubble was reduced since the separation time of oil–water coalescence was gradually shorted. It was a disadvantage of oil–water separation. The oil removal efficiencies of the cyclonic and the airflotation sections were positively correlated. The oil removal efficiency of airflotation section was higher than the cyclonic section. Most of oil droplets in the airflotation section were easily separated, but most of oil droplets in the cyclonic section were too difficult to separate. The proper feeding speed determined by test is $1.5\,\text{m}^3\,\text{h}^{-1}$.

4.2. Effect of the aeration rate

Experiment conditions: $g_l = 1.5\,\text{m}^3\,\text{h}^{-1}$, $p = 0.26\,\text{MPa}$, $q_g = 3.0\,\text{m}^3\,\text{h}^{-1}$, and $f = 95\%$. The impact of aeration rate on the oil concentration of water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column is shown in Fig. 3.

As shown in Fig. 3, with increasing aeration rate, the oil removal rate increased and the oil removal efficiency showed a decreasing trend. When the range of aeration rate was $0–0.5\,\text{m}^3\,\text{h}^{-1}$, the oil removal efficiency of the cyclonic section was greater than the airflotation section. Finally, the oil removal efficiencies of the airflotation section and the whole column tend to be smooth, except that the oil removal efficiency of the cyclonic section dropped a little. On the basis of the slope of three curves on oil removal efficiency, the aeration rate had more influence on the cyclonic section than the airflotation section.

The number of oil–bubble complex is the key factor in the oil–water separation process. The high collision probability between oil drops and bubbles can increase the number of oil–bubble complex. When the aeration rate was under $3\,\text{m}^3\,\text{h}^{-1}$, the number of bubbles increased in the aeration section. The oil removal efficiency continuously increased and the oil concentration of the underflow outlet decreased because the collision probability between bubbles and oil droplets increased. After the aeration rate increased to $3\,\text{m}^3\,\text{h}^{-1}$, the coalescence of bubbles in the cyclonic trend to tempestuous, the smaller diameter bubble which had bigger capacity to capture oil droplets continuously decreased, the number of oil–bubble complex reduced. Therefore, the oil removal efficiency decreased. The aeration rate determined by test is $2.5\,\text{m}^3\,\text{h}^{-1}$.

4.3. Effect of the circulating pressure

Experiment conditions: $g_l = 1.5\,\text{m}^3\,\text{h}^{-1}$, $q_c = 20\,\text{m}^{-3}\,\text{h}$, $q_g = 2.5\,\text{m}^3\,\text{h}^{-1}$, and $f = 95\%$. The circulating pressure impacts on the oil concentration of water outlet, oil removal efficiencies of the cyclonic section, the

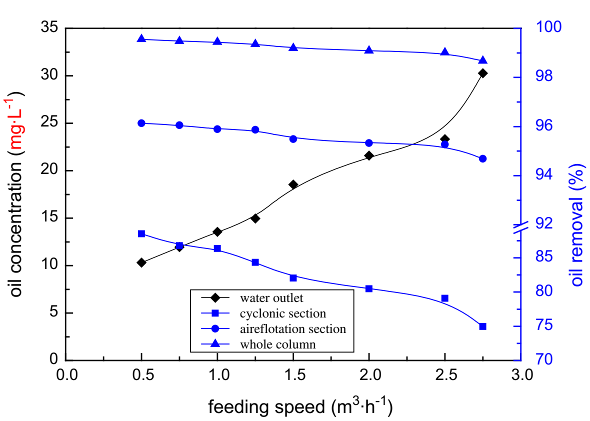

Fig. 2. The influence of feeding speed on the oil concentration of the water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column.

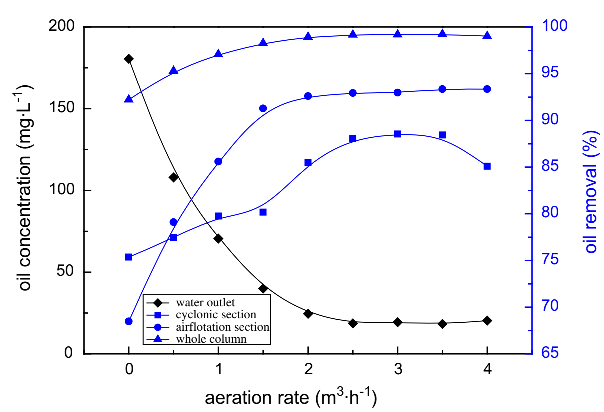

Fig. 3. The influence of aeration rate on the oil concentration of the water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column.

removal efficiencies of the cyclonic section, the airflotation section, and the whole column are shown in Fig. 4.

As shown in Fig. 4, with increasing circulating pressure, the oil concentration of the water outlet decreased and the oil removal efficiency increased continuously. According to the three curves on oil removal efficiency, the circulating pressure had greater impact on the cyclonic section than others.

With the increasing circulating pressure, the oil removal efficiency tended to increase. During the range of suitable pressure, smaller bubble sizes and more quantities were generated because of the higher pressure. That was an advantage of improving the oil removal efficiency of the airflotation section. The circulating pressure can provide suitable energy, which was better for forming oil–gas complex for colliding between oil droplets and bubbles. If the circulating pressure exceeded 0.3 MPa, as the oil droplet was under larger shearing force, small oil droplets were formed easily and the cyclonic separation effect was impacted adversely. The circulating pressure determined by test is 0.28 MPa.

4.4. Effect of the underflow split ratio

Experiment conditions are as follows: $g_l = 1.5\,m^3\,h^{-1}$, $p = 0.26$ MPa, $q_c = 23\,m^3\,h^{-1}$, and $q_g = 2.5\,m^3\,h^{-1}$. The underflow split ratio effect on the oil concentration of water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column is shown in Fig. 5.

As shown in Fig. 5, with increasing underflow split ratio, the oil concentration of the water outlet decreased at first and then continuously increased after underflow split of 85%, the oil removal efficiency remained stable at around 34% and then rapidly decreased after underflow split of 95%. According to the three curves on oil removal efficiency, the underflow split ratio influence on the cyclonic section; the airflotation section and the whole column were similar.

In order to maximally increase the purified outflow of the underflow outlet, water content needs to be reduced. This may decrease the separation efficiency and therefore requires secondary purification. The underflow split ratio determined by test is 95%.

4.5. Effect of the frother consumption

Experiment conditions: $g_l = 1.5\,m^3\,h^{-1}$, $p = 0.26$ MPa, $q_c = 23\,m^3\,h^{-1}$, $q_g = 2.5\,m^3\,h^{-1}$, and $f = 95\%$. The frother consumption impacts on the oil concentration of water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column are shown in Fig. 6.

As shown in Fig. 6, with increasing frother consumption, the oil concentration tended to decrease and the oil removal efficiency tended to increase. Based on the slope of the three curves on oil removal efficiency, the frother consumption had a greater impact on the cyclonic section than the others.

After adding the frother, the bubble size reduced and the bubble quantity increased and the collision probability between bubbles and oil droplets increased. The frother can also increased the quantity of the oil droplets flocs' hydrophobic groups, so the adhesive quantity and quality of the bubble were enhanced and the flotation effect was improved. The decrease of the bubble size and the increase of the bubble quantity were better for oil–water separation.

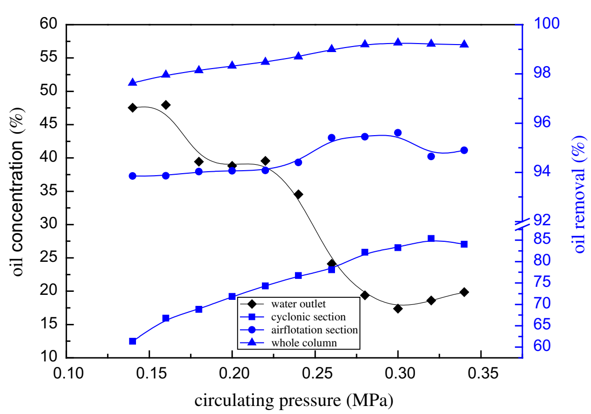

Fig. 4. The influence of circulating pressure on the oil concentration of the water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column.

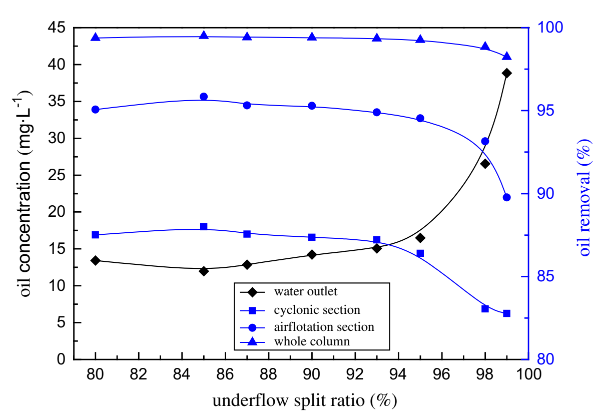

Fig. 5. The influence of underflow split ratio on the oil concentration of the water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column.

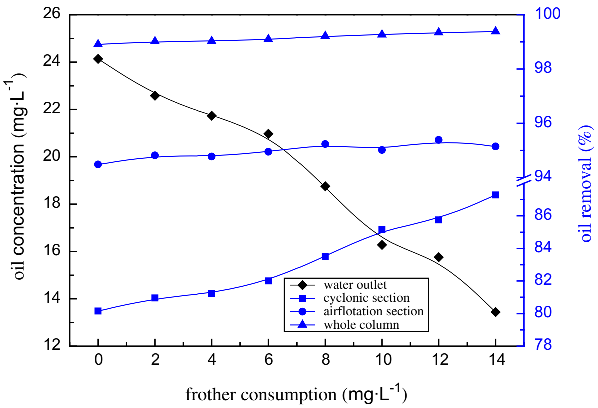

Fig. 6. The influence of frother consumption on the oil concentration of the water outlet, oil removal efficiencies of the cyclonic section, the airflotation section, and the whole column.

In practical industrial application, because more consumption of agentia (such as polyacrylamide) is used in the processing of polymer flooding, the oily sewage is more and more difficult to dispose. The price of frother is also very expensive. So that frother should not be added if the oil concentration of the water outlet meets the requirement. Due to the experimental result, it is not needed to add the frother.

5. Mathematical model of oil removal efficiency

5.1. Mathematical model of oil removal efficiency of the cyclonic section

The operating parameters include the feeding speed g_l, aeration rate q_g, circulating pressure p, and underflow split ratio f are main factors influencing the oil removal efficiency of the cyclonic section. By analyzing these operating parameters and oil removal efficiency (namely the cyclonic separation efficiency R_1), it was found that the cyclonic separation efficiency R_1 can be correlated to the feeding speed g_l, aeration rate q_g, circulating pressure p, and underflow split ratio f, using this cyclonic separation model:

$$R_1 = 6.2356\left(0.0385p^{-0.05413} + 0.0295q_g^{-0.1441} + \frac{0.02161}{4.4356f^{-0.3986} + 3.6250g_l^{-1.4617}}\right)^{-1.1855} \quad (5)$$

The cyclonic separation model shows that the oil removal efficiency R_1 firstly increases and then decreases with the increase of circulating pressure p and aeration rate q_g, but it firstly decreases and then increases with the increase of feeding speed g_l and underflow split ratio f.

5.2. Mathematical model of oil removal efficiency of the airflotation section

The main operating parameters include the feeding speed g_l, aeration rate q_g, and underflow split ratio f. According to the result of the relation between the operating parameters and the oil removal efficiency in the cyclonic section (namely the airflotation separation efficiency R_2), it was found that the airflotation separation efficiency R_2 can also be correlated to the feeding speed g_l, aeration rate q_g, and underflow split ratio f, using this airflotation separation model:

$$R_2 = 93.4619\left(1.4859q_g^{-0.4926} + \frac{0.7253}{0.9095f^{-0.2237} + 0.8053g_l^{-0.8411}}\right)^{-0.1849} \quad (6)$$

According to the airflotation separation model, the oil removal efficiency R_2 firstly increases and then decreases with the increase of circulating pressure p and aeration rate q_g, but it firstly decreases and then increases with the increase of feeding speed g_l and underflow split ratio f.

5.3. Mathematical model of oil removal efficiency of the whole column

The operating parameters include the feeding speed g_l, aeration rate q_g, circulating pressure p, and underflow split ratio f are main factors influencing the oil removal efficiency of the cyclonic section, Based on these operating parameters and oil removal efficiency (namely the whole column separation efficiency R), it was found out that the whole column separation efficiency R can also be correlated to the feeding speed g_l, aeration rate q_g, circulating pressure p, and underflow split ratio f, using this whole column separation model:

$$R = 7.7209\left(0.0013p^{-0.05484} + 0.0965q_g^{-0.182} + \frac{-0.0041}{4.3915f^{-0.8561} + 0.8350g_l^{-0.0933}}\right)^{-1.0759} \quad (7)$$

The whole column separation model shows that the oil removal efficiency R firstly increases and then decreases with the increase of circulating pressure p

and aeration rate q_g, but it firstly decreases and then increases with the increase of feeding speed g_l and underflow split ratio f.

6. Conclusions

The cyclonic separation and airflotation separation have been investigated, both of them being important for the oil–water separation flotation column. Several operating parameters which impact these separation modes were investigated and the best operation conditions were determined. These include a feeding speed of $1.50\,m^3\,h^{-1}$, an aeration rate of $2.50\,m^3\,h^{-1}$, a circulation pressure of 0.28 MPa, an underflow split ratio of 95%, and an oil concentration of water outlet of 16.49 $mg\,L^{-1}$.

The oil removal efficiencies of the cyclonic and airflotation sections were positively correlated. The oil removal efficiency of airflotation section was higher than the cyclonic section. The frother was beneficial to separation, but it can also introduce secondary pollutants that make the oily sewage more difficult to separate. Considering the high price of frother, and experimental results obtained, it was not necessary to add frother in this process.

Three mathematical models of oil removal efficiencies of the cyclonic section R_1 (Eq. (5)), the airflotation section R_2 (Eq. (6)) and the whole column R (Eq. (7)) were established. It shows that the circulating pressure is the key factor in the processing of oil–water separation.

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Nomenclature

C_1 — oil concentration at point 1 ($mg\,L^{-1}$)
C_2 — oil concentration at point 2 ($mg\,L^{-1}$)
C_3 — oil concentration at point 3 ($mg\,L^{-1}$)
q_1 — overflow outlet flow ($m^3\,h^{-1}$)
q_2 — underflow outlet flow ($m^3\,h^{-1}$)
g_l — feeding speed ($m^3\,h^{-1}$)
q_g — aeration rate ($m^3\,h^{-1}$)
p — circulating pressure (MPa)
f — underflow split ratio (%)
R_1 — oil removal efficiency of the cyclonic section (%)
R_2 — oil removal efficiency of the airflotation section (%)
R — oil removal efficiency of the whole column (%)

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