# A SCALE-UP STUDY OF MULTI-STAGE LOOP-FLOW FLOTATION PROCESS FOR OILY WATER TREATMENT

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## ABSTRACT

A Multi-Stage loop-flow flotation column (MSTLFLO®) process is designed for the removal of oil pollutants from wastewater. The MSTLFLO flotation column has shown superior performance in the removal of emulsified oil. Experimentally determined kinetic constants have been correlated with operating conditions in terms of hydrodynamic parameters, including gas holdup, sauter bubble size, and liquid volumetric flow rate. A comparison of performance data obtained in two columns of different sizes (a 12-in and a 4-in column) indicates that a simple geometric ratio of column diameters can be used as the basis for column scale-up.

Key words: Multi-stage, flotation, oily water, kinetic model, scale-up

## 1. INTRODUCTION

In the world, there are enormous amount of wastewater discharged by many industrial sources, including paper mills, petroleum refineries, chemical processing and other manufacturing plants[1, 2]. Among them, oil-bearing emulsion is a very common occurrence. To meet current and future challenges, there is a press need to develop an efficient and economical technique for treating industrial wastewater, especially the oil pollutant, to protect the environment. Flotation process has been recognized as one of the promising technique because of its high separation efficiency, low capital investment and ease of operation [3, 4, 5, 6, 7]. A multistage loop-flow flotation column (MSTLFLO) developed in our laboratory has shown superior performance in the removal of emulsified oil from water.

In the past, the rate of the flotation process is generally assumed to obey the first-order kinetics [7, 8, 9, 10, 11, 12, 13, 14]. However, the results obtained in our laboratory [15, 16] have demonstrated that a none-linear kinetic model can better represent the experimental data than the linear model. As a follow-up, a scale-up study is being carried out for oil removal using two different sizes of the MSTLFLO column.

## 2. EXPERIMENTAL

### 2.1. Equipment

The MSTLFLO flotation process for wastewater treatment is illustrated in Figure 1. Three draft tubes are installed in the column working as three continuous operation stages. Each stage can be viewed as a subset of a bubble column, which shares the operating characteristics of an air-lift reactor. Simulated wastewater is fed into the top stage of the column via a liquid distributor. Air is introduced into the bottom stage of the column through a porous sparger with a mean pore size of 10 micron. Treated water leaves the column from a discharge pipe outlet at the bottom, while oil-laden foam overflows into a foam discharge tank from the top of the column.

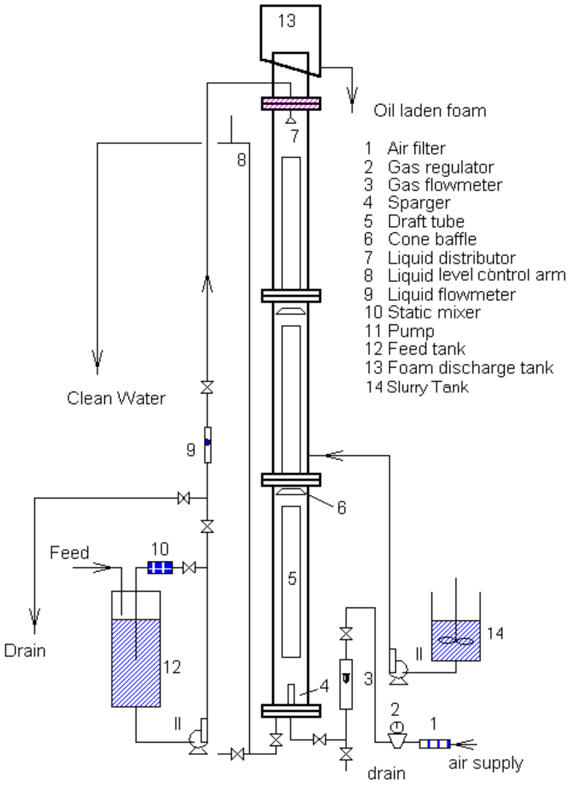

Figure 1 MSTLFLO flotation process

For the scale-up study, a simple geometric scale-up scheme based on the ratio of column diameter is applied. Two different sizes of the MSTLFLO flotation column with similar internal structure have been used: a 4-in column with 0.102 m O.D. and a 12-in column with 0.306 m O.D. Geometric dimensions of major components of these two columns and key operating conditions are listed in Table 1. It is shown that the ratios of two columns diameters and two draft tubes diameters are approximately 3. However, due to the head room limitation in our laboratory, the height of the 12-in column cannot exceed 7 meters. Therefore, the ratio of draft tube height to its diameter in the 12-in column is smaller than that in the 4-in column. It can also be seen that the range of liquid feed rates in the 12-in column is 10 times of that in the 4-in column because the liquid feed rate is directly proportional to the cross-sectional areas of the column. All other operating conditions are kept in the same ranges for the two columns.

Table 1 Geometries and operating conditions of multistage flotation column

| | 4-in Column | 12-in Column |
|---|---|---|
| Outside diameter, m | 0.102 | 0.306 |
| Draft tube diameter, m | 0.076 | 0.203 |
| Height, m | 4.50 | 6.50 |
| Inside stages | 3 | 3 |
| Frother concentration, ppm | 0-40 | 0-40 |
| $V_g$, cm/s | 0-4 | 0-3.9 |
| Gas holdup, % | 25-40 | 25-40 |
| Liquid feed, l/min | 0-1 | 0-10 |

### 2.2 Material and methods

Light mineral oil supplied by Fisher Scientific Company is used as oil phase simulator. Oil concentration is analyzed with an oil content analyzer, OCMA-220, Horiba. In all experiments, 2-ethyl-1-haxanol (2-EH), 99+%, supplied by Aldrich chemical company is used as the frother agent. In order to obtain a stable oil emulsion with oil concentration up to 500 ppm, the oil-water mixture is prepared by forcing it to recycle through a static mixer for at least 90 minutes.

## 3. PROCESS KINETICS

Our previous studies [15, 16] show that the rate of oil removal in MSTLFLO column obeys the non-linear kinetics and can be expressed as:

$$-\frac{dC}{dt} = K\frac{C - C_\infty}{t} \qquad (1)$$

where $C$ and $C_\infty$ are concentration and asymptote concentration of oil; $t$ is flotation time and $K$ is kinetic constant. Recognizing similar hydrodynamic behaviors among all three stages along the MSTLFLO column, kinetic behaviors in the bottom stage can be used to represent that of the entire column. The kinetic constants thus obtained are correlated with experimentally measured hydrodynamic parameters, which include gas holdup, $\varepsilon$, bubble Sauter diameter, $d_{32}$, superficial gas velocity, $V_g$, and liquid volumetric flow rate, $Q_L$ [15, 16,17]:

$$K = \frac{a\varepsilon^b Q_L^c}{d_{32}{}^d} \qquad (2)$$

where $a$, $b$, $c$ and $d$ are empirical correlation constants (impact factors).

## 4. RESULTS AND DISCUSSION

### 4.1 Excellent performance of oil removal

The results of oil removal experiments in the 4-in and 12-in columns are shown in Figure 2 and 3, respectively. It can be seen that the performances in two columns are very similar and greater than 90% oil removal efficiency can be achieved. At a given superficial gas velocity ($V_g$), higher frother concentrations ($C_F$) yield greater oil removal efficiency, while higher superficial gas velocity gives better oil removal efficiency at a given frother concentration.

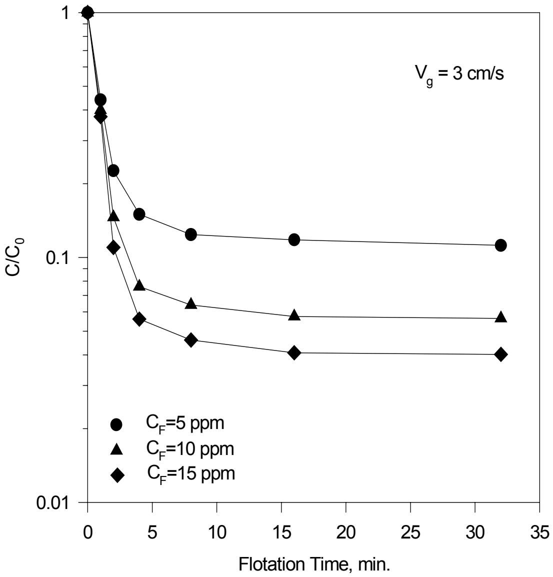

Figure 2 Oil removal experiments in the 4-in column

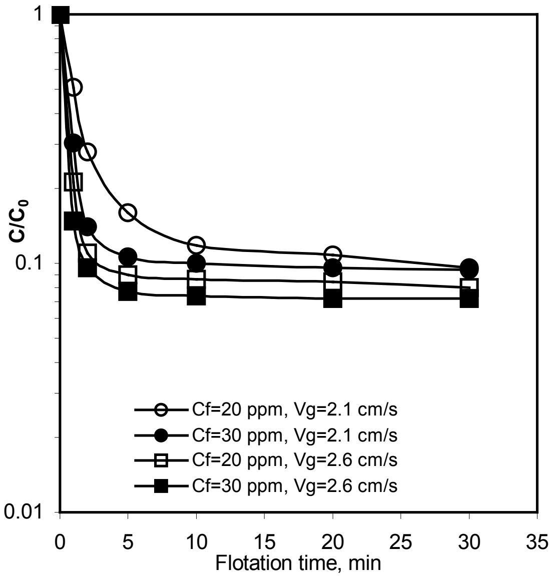

Figure 3 Oil removal experiments in the 12-in column

### 4.2 Kinetic constant for oil separations

Experimental data in both 4-in and 12-in columns obey the same none-linear kinetic model as expressed in Equation (1). The calculated kinetic constants for both 4-in column, $K_4$, and 12-in column, $K_{12}$, are summarized in Table 2. As defined, a large $K$ indicates a fast oil removal rate. From Table 2, it is seen that increasing superficial gas velocity $V_g$ and frother concentration $C_F$ will increase $K$ values. It is also noted that under the comparable operating conditions in two columns, for example, at 20 ppm frother concentration and 2.0 –2.1 cm/s superficial gas velocity, the $K$ value in the 4-in column is larger than that in the 12-in column. This difference is most likely due to the different ratios of draft tube length to diameter in these two columns, as previously reported [16, 17].

Table 2 Summary of kinetic constants

| 4-in column | | | 12-in column | | |
|---|---|---|---|---|---|
| $V_g$, cm/s | $C_F$, ppm | $K_4$ | $V_g$, cm/s | $C_F$, ppm | $K_{12}$ |
| 1.0 | 15 | 0.814 | 1.3 | 20 | 0.658 |
| 1.0 | 20 | 1.394 | 1.3 | 30 | 0.914 |
| 2.0 | 15 | 1.83 | 2.1 | 20 | 1.25 |
| 2.0 | 20 | 1.88 | 2.1 | 30 | 1.35 |
| 3.0 | 15 | 2.21 | 2.6 | 20 | 2.24 |
| 3.0 | 20 | 2.23 | 2.6 | 30 | 2.30 |

### 4.3 Correlations of kinetic constants with operating parameters

Kinetic constants are correlated with operating parameters using Equation (2). The impact factors are listed in Table 3. The values of coefficients of determination, $R^2$, are greater than 95%, indicating the correlations fit experimental data very well for both 4-in and 12-in columns. The values of impact factors correspond to the influence of associated operating parameters on the kinetic constants. In Table 3, it can be seen that the impact factor $d$ is found to be the largest, indicating bubble size, $d_{32}$, is the most crucial factor to rate of oil removal. The values of impact factors $b$ and $c$ are comparably much smaller than $d$, which implies that gas holdup and volumetric flow rate have relatively less impacts on the oil removal kinetics. The differences in impact factors between 4-in and 12-in column can be attributed to the limitation imposed on the length of the draft tubes used in the 12-in column, which results in a smaller length to diameter ratio of the draft tube in the 12-in column than that in the 4-in column.

Table 3 Summary of impact factors to oil removal kinetics

| | $a$ | $b$ | $c$ | $d$ | $R^2$ |
|---|---|---|---|---|---|
| 4-in column | 1.003 | 0.602 | 0.519 | 1.150 | >95% |
| 12-in column | 0.191 | 0.664 | 0.351 | 1.601 | >98% |

### 4.4 Scale-up design

In our scale-up study, the design of 12-in MSTLFLO column is based on the ratio of column diameters of the 12-in and the 4-in column. The experimental results obtained in the 12-in column compare favorably with that in the 4-in column in terms of the oil removal efficiency and kinetics as well as the operating capacity. Consequently, such a simple geometric scale-up scheme can be extended to future scale-up for the design of larger columns. However, the geometric scale-up of the draft tube, particularly its length to diameter ratio should be properly considered.

## 5. CONCLUSIONS

A simple geometric scale-up scheme is applied to the design of a 12-in MSTLFLO column in term of the ratio of column diameters of the 12-in and the 4-in column. Both 12-in and 4-in columns have shown comparable superior performance in the removal of emulsified oil. Experimentally determined kinetic constants have been correlated with operating conditions in terms of the same set of hydrodynamic parameters. These results validate the use of a simple geometric ratio as the basis for scale-up of the MSTLFLO column design for future commercial applications.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| $a, b, c, d$ | Empirical impact factor | $C$ | Concentration (ppm) |
| $C_F$ | Frother concentration (ppm) | $C_\infty$ | Asymptote concentration |
| $d_{32}$ | Sauter mean diameter | $K$ | Oil removal kinetic constant |
| $K_{4,12}$ | Kinetic constants of the 4-in and 12-in column | $Q_L$ | Volumetric flow rate of liquid circulation ($m^3s^{-1}$) |
| $V_g$ | Superficial gas velocity ($ms^{-1}$) | $\varepsilon$ | Gas holdup (%) |

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