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OIL-WATER SEPARATORS HYDRAULIC EFFICIENCY ANALYSIS USING TRACER STUDIES

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Abstract

This study on the effect of the dispersion coefficient on the experimental optimization of hydraulic efficiency of oil-water separation is aimed at determining the effect of variations in separator geometric configurations and hydrodynamics on the hydraulic efficiency in the treatment of oil-contaminated wastewater. Three sets of experimental rectangular model separators of varying lengths and constant width were constructed using transparent fibre glass sheets with each set consisting of four (4) numbers of different model separators. For each separator, an inlet baffle and outlet baffle were installed, 0.5m from the inlet and outlet respectively. For a single outlet baffle, the best performance of 97.83% efficiency was obtained from a baffle location of 3.1m from the inlet for a model separator length of 3.6m and flow rate of 0.004m^3/min. Tracer studies were employed in determining the dispersion coefficient values. It was generally observed that the separator efficiencies increase as the detention time increases. The detention time increases as the separation volume and inlet flowrate decrease. The number of baffles and their positioning affects the separation process as the fraction of dead sections was significantly reduced from 0.1339 for a single baffle position to 0.0009 for a triple baffle position for a flowrate of $0.02 \, m^3/min$ in model A3-1

1. Introduction

Oil waste is a common pollutant in most industries. Its removal from water, particularly wastewater continues to pose serious environmental challenges. It affects aquatic life and hinders the self-purification of streams. It is a common practice to use separator vessels to separate oil from water by gravity. In gravity separation, mixtures are separated by the effect of gravity force on the different liquids based on their densities. Factors such as the shape and position of inlet and outlet baffles, tank geometric design, and fluid mixture viscosity influence the hydraulic performance of reactors such as oil-water separators (Kjellstrand et al., 1999, Matar et al., 1989). Proper design of oil-water separator vessels requires proper analysis to determine the fluid behaviour as they travel through the reactor's vessel. The knowledge of the fluid flow behaviour obtained from tracer studies and particle separation efficiency is vital in the design and optimisation of oil-water separators (Juan et al., 2018). Dispersion models can be used to characterize real flows having small deviations from plug flow in reactor vessels. In dispersion studies, the characterisation of oil-water separator vessel can be achieved by analysing the residence time distribution curves obtained from tracer studies to determine the hydraulic performance.

Residence time is the time taken for particles of a fluid mass passing through a separator vessel to exit the vessel from the inlet. This can be determined by monitoring the flow path and exit time of a soluble substance called tracer injected at the vessel's inlet. (Rodrigues, 2020).

A system approaches plug flow when the mean residence time (MRT) obtained from tracer studies is close to the theoretical time ($equation\ 4$) and having minimal dispersion. In many systems, some particles may exit the reactor vessel before the theoretical detention time. This situation is known as short-circuiting and it's caused by bypassing of some fluid particles and thus, indicates the presence dead zones which reduces the efficiency of separators.

The aim of the study was to determine the dispersion coefficient of various flow configurations in order to optimize the hydraulic efficiency of oil-water separators.

Tracer studies

The basic principle of a tracer investigation is to mimic a phase of the flow using a tracer and follow it through a vessel. Results of the study assist with optimizing chemical usage, verify vessel internal performance and enhance maintenance and design changes (Spencer, 2016).

Tracer residence time distribution(RTD) is identical to the RTD of a fluid particle that enters the vessel at the same time as the amount of tracer exiting a reactor for a pulse tracer input into a reactor at a particular time is proportional to the amount of fluid exiting the reactor at that same time, if both tracer and fluid entered the reactor at the same time. RTD is the normalized outlet condition of a tracer with time when the tracer is introduced into a reactor as a pulse input (Rodrigues, 2020). It is a measure used to detect how fluid flow behaviour advance towards the best possible condition (Bérard et al., 2020).

Plug flow reactors are elongated basins that are mixed radially and axially but with non-uniform mixing in the longitudinal direction (Dey, Dipa; Herzog, Amanda; Srinivasan, 2007). The effect of this non-uniform mixing are usually a function of short circuiting and the presence of dead zones. This effect can be determined by plotting the concentration-time graph from a tracer studies experiment. Advection dominates in a plug flow reactor such that, conservative tracers introduced at the reactor inlet remains intact until it leaves the reactor outlet (Dey, Dipa; Herzog, Amanda; Srinivasan, 2007).

1. Tracers can be used to detect leaks in vessels, calibrate flow meters, and access difficult points in separator vessels when efficiently carried out. RTD can be used in evaluating the performance of non-ideal reactors as it helps in the diagnosis of the dispersion and dead zones in plug flow reactors as well as by-passing and stagnant zones in stirred tanks reactors (Sendhil et al., 2012). The ratio of the mean residence time to that calculated from tracer studies can be used to determine the hydraulic efficiency of a reactor. Hafskjold, Morrow, Celius, and Johnson (1994) opined that this ratio is equal to one (1), for plug flow.

2. Research method

Model Separator Vessels

Three transparent model separatorSET1, SET2 and SET3 of widths 0.4m, 0.45m and 0.5m respectively, were used for this research. The separators were designed based on API design standard with a depth of 0.175m. For each set, the length was varied as 2.4m, 2.8m, 3.2m and 3.6m. Baffle positions for each separator was also varied based on the length. Each separator model configuration was then subjected to varying flowrates of

$0.004m^3/min, 0.008m^3/min,\ \ 0.012m^3/min,\ \ 0.$

to determine its effect on the hydrodynamics and oil removal efficiency on an oil-water separation process.

Separation Process

The separator model was designed to remove free oil from the mixture of crude oil and water. The fluid mixture enters the separator through the inlet, hits the inlet diverter (inlet baffle) placed 0.5m from the inlet, and flows downward. As the liquid flows through the separation chamber, the oil rises, leaving the oil/water interface. As the oil globule rises by gravity, the water phase remains at the vessel's bottom and subsequently goes out of the separator through the water outlet. An outlet baffle was placed 0.5m from the outlet which helps to trap the separated oil for subsequent removal by skimming.

Table 1 gives the description of baffle position for multiple baffles used for the determination of the effect of number of baffles on separator performance.

Table 1: Variation in Outlet/Oil Retaining Baffle Positions

Separator Model	GEOMETRY		Oil Retaining Baffle Positions from Inlet		
	Length	Width	1	2	3
A3-1	3.2	0.4	1.2	1.9	2.7
A4-1	3.6	0.4	1.4	2.3	3.1

The oil content in both inlet and outlet were measured using a multi-purpose HACH DR 6000 UV-VIS Spectrophotometer. The separator efficiency was calculated using the equation (3.1) below.

$$Efficiency\ E(\%) = \left(1 - \frac{C_{in}}{C_o}\right) (1)$$

$$where C_{in} and C_o are inlet and outlet concentrations of oil in water respectively.$$

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Residence Time Distribution

Instead of using hydraulic retention time (HRT), the residence time distribution (RTD) obtained by Tracer studies can better explain the flow condition in a flow medium like oil-water separator. It consists of measuring the time spent for oil to travel through the vessel using a tracer compatible with oil. The measurement of residence time distribution was carried out by pulse injection of sodium chloride (NaCl) salt-water brine into the inlet stream of oil-water separator. Few researchers in the past have estimated RTD in oil-water separation. It is given as follows.

$$t = Exit\ time\ from\ separator - Entry\ time\ into\ separator \quad (2)$$

$$t = \frac{Distance\ traveled\ by\ waste\ water\ in\ separator}{Velocity\ of\ waste\ water\ in\ separator} \quad (3)$$

$$t = \frac{Volume\ of separator}{flow\ rate\ in\ separator} t = \frac{V}{Q_{in}} \quad (4)$$

For this research work, the mean residence time was designated as t and computed using equation (4)

Preparation of Tracer

Sodium chloride (NaCl) salt-water brine of 20800mg/l was produced by mixing 250g of common salt with 1200ml of produce water. Two (2) grams of food grade dye and hydrogen sulphide(H_2S) were then added for ease of monitoring the tracer as well as tag the oil phase. Fifty millilitres(50ml) of this tracer mixture were injected at the tracer injection point during the separation process.

Dispersion Characteristics Determination using Tracer studies

Tracer studies can give a valuable insight on the bulk fluid behaviour inside the separator. The method of sampling for tracer in this research was the constant-distance variable-time method.

In this method, a blank sample was first collected at the inlet seconds after injecting 50ml of the tracer mixture as pulse input at the tracer injection point. The flow through the separator was monitored by observing the tracer dye. At the outlet, samples were collected at regular time interval immediately the tracer arrived, until such a time it was assumed that all the tracers have completely flown out. The flow through the separator was continuous as inflow from the elevated tank was simultaneously allowed into the separator. This process was repeated for all flow configurations to determine their effect on the separator efficiency. The concentration of salt tracer at the end of each experiment was determined by titrating 25ml of the sample with silver nitrate solution. Before titration, two drops of potassium chromate indicator ($1g\ K_2CrO_4$ plus 20ml distilled water) were added to the 25ml of sample in a conical flask.

Concentration of NaCl tracer for each separation process can be calculated using equation (3.8)

$$NaCl\ concentration\ C\ (mg/l) = \frac{(a-b) \times N \times 3450}{ml\ of\ sample\ used} \qquad (5)$$

$$where \quad a = ml\ of\ silver\ nitrate\ in\ blank\ sample$$
$$b = ml\ of\ silver\ nitrate\ in\ sample = \ varies$$
$$N = Normality\ of\ silver\ nitrate = 0.0141$$

Tracer studies enables the determination of the residence time since the actual residence time in an ideal plug flow reactor is the same for all particles and identical to the mean residence time.

It should be noted that all concentrations results obtained from tracer tests were subtracted from the base-flow concentration which is the original salt concentration of the oil-water mixture stream before tracer injection. The titration result for the blank sample was 3.5mg/l.

Dispersion Coefficient

The dispersion coefficient was computed based on the Leverspiel and Smith (1957) moment approach as reported in Agunwamba (2001). For each flow configuration, the dispersion coefficient was calculated using equation (8) but first, the average flow time (θ) was computed using equation (6), followed by the normalized variance (σ) given in equation (7). the normalized variance is required for computation of dispersion coefficient as given in equation (8)

$$\theta = \frac{\Sigma tC}{\Sigma C} \qquad (6)$$

$$where\ \theta = average\ flow\ time,\ t = tracer\ residence\ time$$
$$C = Concentration\ of\ salt\ tracer\ at\ the\ sampling\ point$$

$$\sigma = \frac{1}{\theta}\left[\frac{\Sigma t^2 C}{\Sigma C}\right] \qquad (7)$$

$$.\varepsilon = \frac{1}{8}\left(\sqrt{1+8\sigma^2} - 1\right) \quad (8)$$

$$where\ \sigma = Normalized\ Variance$$
$$\varepsilon = Dispersion\ number$$

The theoretical mean residence time computed from equation (4), while he actual mean residence time (t_a) calculated from tracer studies is given in equation (9)

$$t_a = \frac{\Sigma tC}{\Sigma C} \quad (9)$$

The hydraulic efficiency is therefore calculated as the ratio of the actual mean residence time (t_a) to the theoretical mean residence time (t)

$$Hydraulic\ efficiency = \frac{t_a}{t} = \frac{\frac{\Sigma tC}{\Sigma C}}{\frac{V}{Q_{in}}} \quad (10)$$

Where $t = vessel\ particles\ residence\ time$ $Q_{in} = inlet\ flowrate$ $V = effective\ volume\ of\ separator$ $C = salt\ concentration\ in\ tracer$

The inclusion of hydraulic efficiency in oil-water separation helps in determination of separator performance as well as the active and dead volume for each vessel configuration when combined with removal efficiency.

The fraction of the separator volume that is dead is the ratio of the dead volume to the total volume as given in equation (11)

$$f_d = \frac{V_d}{V} \quad (11)$$

$$f_d = \frac{Q_{in}(t - t_a)}{Q_{in} t} \quad (12)$$

$$f_d = 1 - \frac{t_a}{t} \quad (13)$$

Where $V_d = dead\ volume$

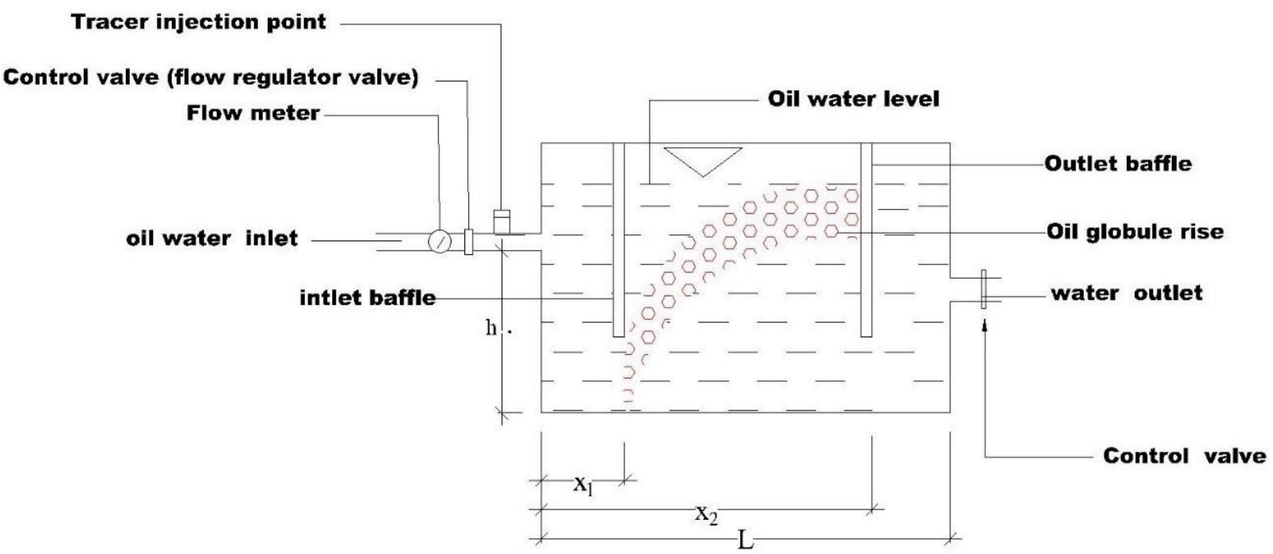

Figure 1: Model schematic diagram of oil-water separator showing Tracer Injection Point

3. Results and discussion

Result show that the dispersion coefficient generally decreases as the flowrate increases as shown in figures 2 and 3. As the dispersion coefficient increases, the separator performance increases as shown in Table 2, 3, and 4..

A plot of the concentration-time graph (Figure 4) shows some undulating sections(short circuiting) caused by by-passing and a long tail (dead sections) for separators of length 2.4m and 2.8m for a flowrate of $0.02m^3/min$ indicating that higher inlet flowrate and small separator length creates problem for oil-water separators. However, this was not the case when the separator length was increased to 3.2m and 3.6 as better concentration-time graphs were produced due to increase in detention time. The dispersion coefficient values obtained from the concentration-time graph of Figure-4 were 3.44, 3.714, 3.571 and 3.992 for separators of length 2.4m, 2.8m, 3.2m and 3.6m respectively for a constant flowrate of $0.02m^3/min$ showing that dispersion coefficient increases as separator length increases.

Figure 5 shows that smoother and better curves were obtained for all flowrate with a separator length of 3.2m. it therefore be said that higher values of length and lower values of flowrate produced better values dispersion and separation efficiency

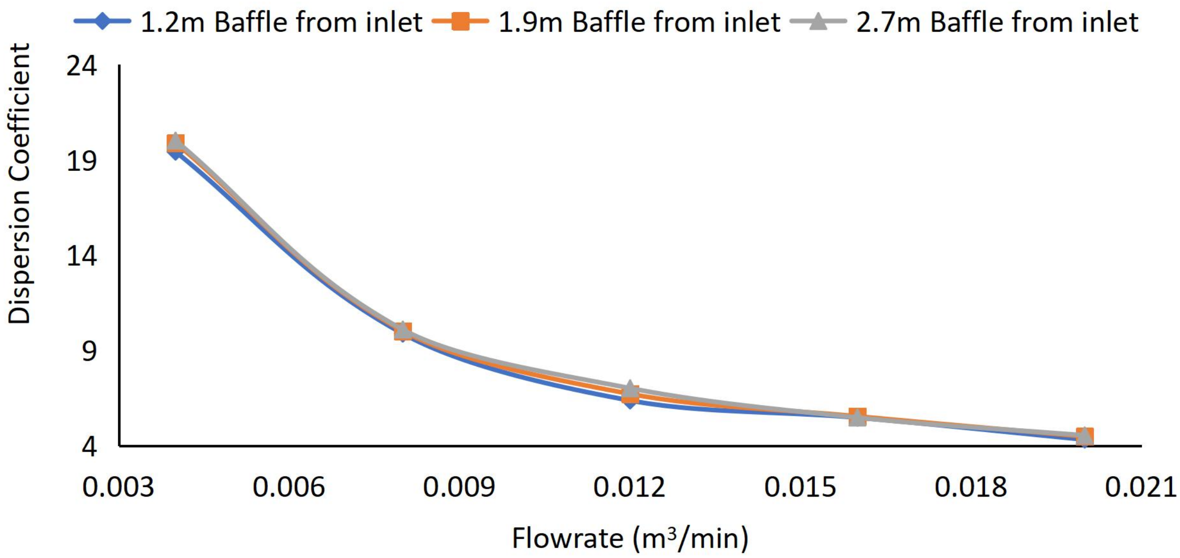

Figure 2: Variation in Dispersion Coefficient due Baffle position Set 1 Model A1-3

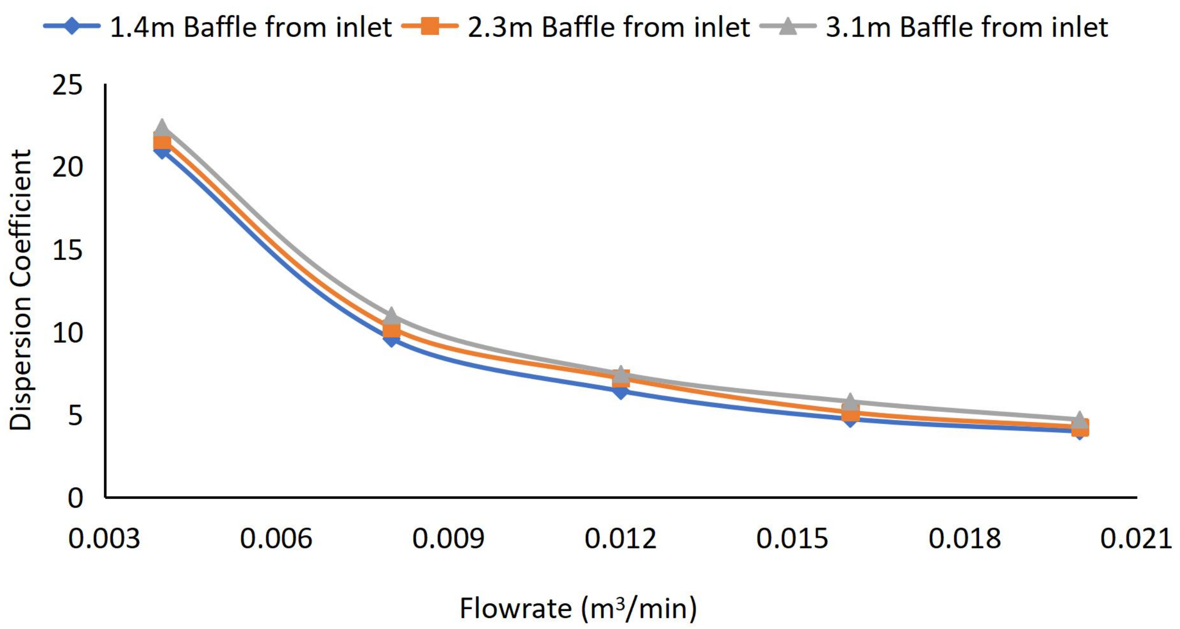

Figure 3: Variation in Dispersion Coefficient due Baffle position Set 1 Model A1-4

Table 2: Effect of Dispersion Coefficient on the Separator Efficiency for SET 1

Inlet flow rate (Q) (m^3/min)	Length (m)	Cross Sectional Area (m^2)	Flow Velocity (m/min)	Residence Time (s)	Dispersion Coefficient	Inlet sample (mg/l)	Outlet sample (mg/l)	Efficiency (%)
0.004	2.4	0.07	0.05714286	2520	14.9953	10.78	1.71	92.7403
0.004	2.8	0.07	0.05714286	2940	17.5526	10.95	1.64	93.5678
0.004	3.2	0.07	0.05714286	3360	20.0104	11.48	1.58	94.4656
0.004	3.6	0.07	0.05714286	3780	22.3564	11.02	1.51	94.9102

Table 3: Effect of Dispersion Coefficient on the Separator Efficiency for SET 2

Inlet flow rate (Q) (m^3/min)	Length (m)	Cross Sectional Area (m^2)	Flow Velocity (m/min)	Residence Time (s)	Dispersion Coefficient	Inlet sample (mg/l)	Outlet sample (mg/l)	Efficiency (%)
0.004	2.4	0.07875	0.05079365	2835	16.8294	10.75	1.71	92.7179
0.004	2.8	0.07875	0.05079365	3307.5	19.3354	11.95	1.65	94.0639
0.004	3.2	0.07875	0.05079365	3780	22.218	10.35	1.47	94.9733
0.004	3.6	0.07875	0.05079365	4252.5	24.8202	12.95	1.38	96.8201

Table 4: Effect of Dispersion Coefficient on the Separator Efficiency for SET 3

Inlet flow rate (Q) (m^3/min)	Length (m)	Cross Sectional Area (m^2)	Flow Velocity (m/min)	Residence Time (s)	Dispersion Coefficient	Inlet sample (mg/l)	Outlet sample (mg/l)	Efficiency (%)
0.004	2.4	0.0875	0.04571429	3150	18.3563	10.05	1.55	93.9227
0.004	2.8	0.0875	0.04571429	3675	21.6304	10.95	1.47	95.2764
0.004	3.2	0.0875	0.04571429	4200	24.833	11.25	1.38	96.2927
0.004	3.6	0.0875	0.04571429	4725	27.6465	11.12	1.22	97.8261

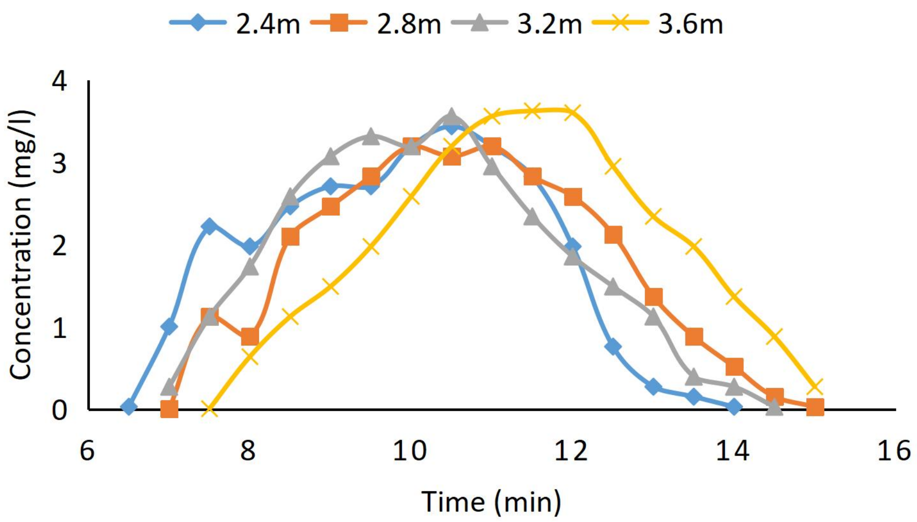

Figure 4: Variation in Tracer Concentration with Time for separator with a flowrate of 0.02m^3/min and width of 0.4m for different separator lengths

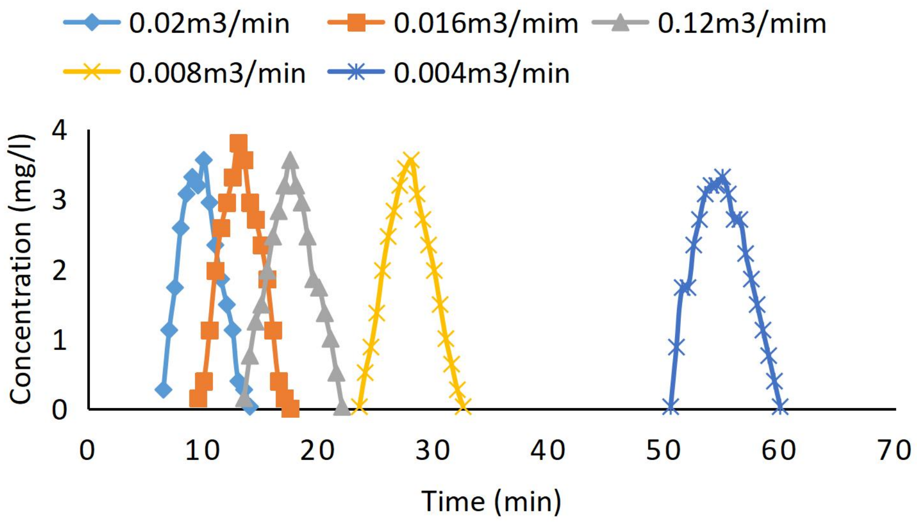

Figure 5: Variation in Tracer Concentration with Timeof separator for different flowrates and constant with and length of 0.4m and 3.2m respectively

Effect of Dead Zones on Separation Efficiency

The volume of dead section also significantly decreased as the flowrate decrease and the length increased.

Dead zones are stagnant portions of a separator with poor or no mixing and so lead to a reduction in the separator available effective volume. This could be caused by the separator's geometric configuration, or the nature and location of certain internal features, or the liquid mixture flow hydrodynamics or a combination of any of the three conditions. To determine how this affect oil-water separator performance, tracer studies for different baffle position and a combination of baffles was carried out. The hydraulic efficiency which the ratio of the theoretical detention time (θ) to the actual detention time as given in equation (3. For single separation baffle (oil retaining baffle) position, results show that the least fraction of dead zone of 0.0201 for a baffle of 2.7m from inlet and a flowrate of 0.004m^3/min, while the highest values of 0.01396 was observed for baffle location of 1.9m and flowrate of 0.02m^3/min.

4. **Conclusion**

Tracer studies was used in monitoring the separation process of oil from water in the oil-water mixture flow stream. The tracer response curve showed the liquid particles behaviour as they flow through the separator. It can be said that the separator efficiency increases as the separation volume increases and as separation baffle location from inlet increases.

Baffles have been known to optimize oil-water dispersion, promote laminar flows, enhance uniformity of flow, increase fluid particle residence time in reactors, and improve separator performances. Increase in the number of baffles leads to increase in separator performance especially when the baffles are positioned at a significant distance from the inlet. Increase in baffle number, increases the uniformity of flow in oil water separator and reduces the dead volume

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