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OPTIMUM COALESCENCE PLATE ARC LENGTH FOR REMOVAL OF OIL DROPLETS FROM WASTEWATERS

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Abstract

Aspects on the arc length of coalescence plates of a oil-water separator as determinant factors for removal of oil droplets from wastewaters were investigated. The primary component of the separator consists of a series of concave and convex shaped coalescence plates to form multiple angles plate arrangement for enhancement of oil droplet coalescence onto the plates. Experimental results were obtained using different overflow rates and different arc lengths of coalescence plates, and were statistically evaluated. As a result, a series of mathematical equations pertaining to oil removal efficiencies from wastewaters were formulated. The predicted and observed data were compared, and optimal coalescence plate arc lengths for maximum oil droplets removal from wastewater at different flow rates were determined. It was also found that coalescence plate arc length had a more significant effect on oil removal efficiency at high overflow rate than at low overflow rate, i.e. oil removal efficiency dropped with reducing coalescence plate arc length. It was also concluded that removal efficiency of emulsified oil droplets from wastewater was strongly correlated to the system's overflow rate and horizontal projection of arc coalescence plate area.

Keywords: Optimum, Coalescence, Arc Length, Oil Droplets, Wastewaters

Nomenclatures

C_i	Influent oil concentration (mg.L^{-1})
C_o	Effluent oil concentration (mg.L^{-1})
C	Arc plate chord length (m)
d	Oil droplet diameter (m)
E	Oil removal efficiency (dimensionless)
g	Acceleration due to gravity (m.s^{2})
G	Velocity gradient (s^{-1})
$Larc$	Arc plate length (m)
$L_{rel.}$	Relative length (m)
m	Arc plate middle ordinate (m)
r	Fraction of over flow rate to the rising velocity (dimensionless)
v_o	Overflow rate (m.s^{-1})
v_r	Rising velocity of oil droplet (m.s^{-1})
Greek Symbols	
θ	Angle of inclination (degree)
Δ	Arc plate central angle (degree)
μ	Dynamic viscosity of continuous liquid (Pa.s)
ρ	Mass density of continuous liquid (kg.m^{-3})
ρ_o	Mass density of the oil droplet (kg.m^{-3})
Subscripts	
a,b,c	Model parameters

1. Introduction

Continuous growth of population and rapid industrial development leads to rapid increase of oil and grease (O&G) discharges into the receiving waters. As a result, more stringent effluent discharge standards were introduced in recent years in the ASEAN region [1]. At present, simple O&G removal systems are often inadequate and more complex or sophisticated systems are either too expensive or too maintenance intensive [2].

Gravity separation is one of the widely used unit operations for removal of O&G from wastewaters. The performance of a gravity oil-water separator is dependent on the rising velocity of the individual oil droplets and system surface overflow rate [3]. Generally, a typical coalescence plate separator has a relatively low overflow rate and is attained by the application of parallel plates whereby oil droplets can be collected after having risen in a short distance. Coalescence of oil droplets will then occur and are usually removed by using tilted plates. Theoretically, efficiencies of the process were investigated by Yao [4] and Tikhe [5] who demonstrated that removal efficiencies were partially dependant by system's overflow rates. Recently, Law et al [6] developed a separator for removal of physically emulsified and free oils from wastewaters by using a series of coalescence frustums. This is a centre-feed up flow circular separator equipped with a specially designed a vertical perforated inlet pipe distributor [7].

A number of different plate shapes and designs are commercially available ranging from simple flat type to complicated corrugated structures. Although oil-liquid separation technologies have been studied extensively, few aspects related to plate separators appear to be under-studied. Firstly, the relation between separation efficiency and plate shape geometry was not studied, and secondly, there appears to be a critical value for the droplet diameter, whereby smaller droplets cannot be separated at all by a plate separator. In contrast to the plate separators, a flat plate further complicates the understanding of oil removal efficiency due to 1) surface slip, 2) effects of shear with the oil droplets experiencing re-suspension, and 3) dispersion of oil droplets. In this study, the horizontal projection of the plate area was considered since theoretically, inclination of coalescence plate leads to a marginal increase in overflow rate.

This paper reports on the investigation outcomes resulted from further theoretical considerations and experimental works on multiple angles parallel arc coalescence plate separators. Some constructive details including innovative variations in the inlet and outlet construction were investigated with respect to oil droplets or emulsified oils removal efficiencies from wastewaters.

2. Theoretical Analysis

The mechanisms of oil droplets removal from a liquid by gravity separation include the principles of Stockes' Law [8] and Boycott effect [9]. Separation of oil droplets from water is a liquid-liquid separation carried out almost exclusively by gravity separation, either natural or enhanced, using floatation of the oil droplets to remove it from water. Natural gravitational separation is carried out in American Petroleum Institute (API) separators in large tanks [10]. Oil in water is characterised by a spectrum of droplet sizes. The droplet size that must be removed to attain a given effluent concentration depends on the oil specific gravity, concentration and average droplet size present. Design of an enhanced gravity separator size employs the mechanism of the rise velocity υ_r, is given by Stockes' Law [8]:

$$v_r = \frac{g}{18\mu}(\rho_o - \rho)d^2 \quad (1)$$

In the 1920's, Boycott noticed that blood cells settled faster in test tubes that were inclined than in tubes that were straight up or vertical. Acrivos et al [9] developed a theoretical basis, but the general concept is not difficult to grasp. In the event that settler is inclined, the falling particles and rising liquid get out of each other's way (Fig. 1). In a vertical tube, particles settling displace fluid that must rise. An element of this fluid passes past more particles and has to accelerate and decelerate depending on whether its path is wide or narrow [9].

Fluid elements in the inclined tube escape quicker from the particles and flow more easily, and as the particle suspension gets more concentrated it also gets denser [9]. This provides more driving force for settling. The net effect is that the particles slide down along the wall while the clear liquid flows upward with less interference than in the vertical tube [9]. The vector arrows for the enlarged view are the same at the start, but eventually the inclined tube gets the particles near the wall where their direction changes. In this region, they are denser than in the vertical tube, and the liquid has a shorter distance to escape from them [9].

In horizontal separation tank, unlike an up flow one, some percentage of the particles with the υ_r less than υ_o will be removed [11]. The geometrical arrangements (concave and convex) plate shapes would enhance the coalescence of oil droplets and therefore lead to improved separation efficiency as well as once the straight plate been arched then the curved plate will provide extra plate length which consequently leading an improvement on removal efficiency.

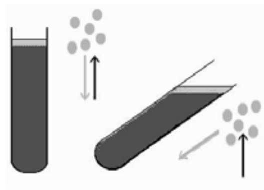


Fig.1. Comparison of Particle Settling in A Vertical and An Inclined Tube [9].

3. Experimental Work

A schematic laboratory experimental setup is illustrated in Fig. 2. The proposed system took the shape in rectangular settling basin embedded with multiple angles parallel arc coalescence plates. The system was designed to remove oil droplets with sizes ≥10 μm in diameter. The primary function of the mixing tank in this experiment was to physically mix the oil droplets with water to produce a solution containing physically emulsified and free oils. The mixing tank was equipped with a typical agitation process vessel or a cylindrical vessel with a vertical axis having a capacity of approximately 200 liters per day (L/d). The mixing tank acted as a rapid mixing tank using mechanical agitators to impart power to the water to produce high shear, turbulence with velocity gradient of approximately 700 sec^{-1}.

The influent oil concentrations were prepared in the range of 100 to 1,000 mg/L (0.1 to 1.0 $kg.m^{-3}$). The oil concentrations in water were determined using a pre-calibrated oil-in-water analyzer (Model OCMA-310, HORIBA) [12]. The oil content analyzer deploys infrared adsorption method to measure oil content in water, and oil dispersed in water is extracted by a solvent with its molecular structure as $CI(CF_2\text{-}CFCI)_2CL$. The oil concentration in a sample was measured by the changes in the amounts of infrared adsorption in the 3.4 to 3.5 μm wavelength range of the extracted liquid. The oil analyzer is a non-dispersive infrared analysis meter that allows a relatively very sensitive analysis since the cell length is adjustable the equipment has the ability to take measurements without losing elements with low boiling points [12].

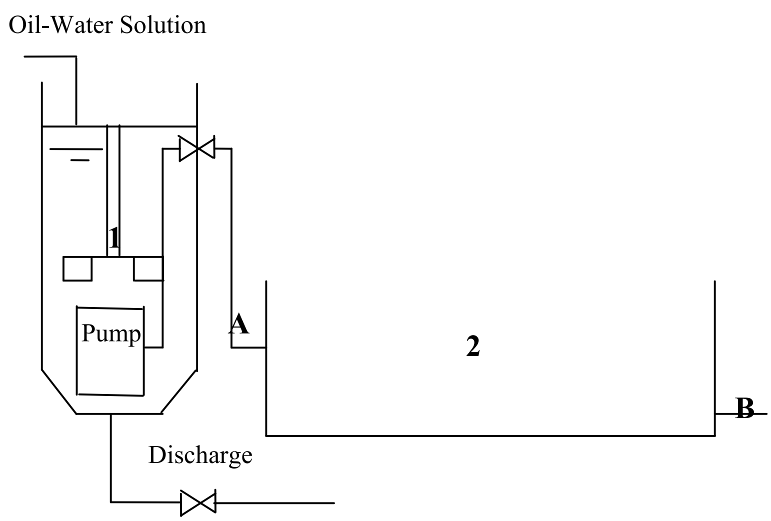


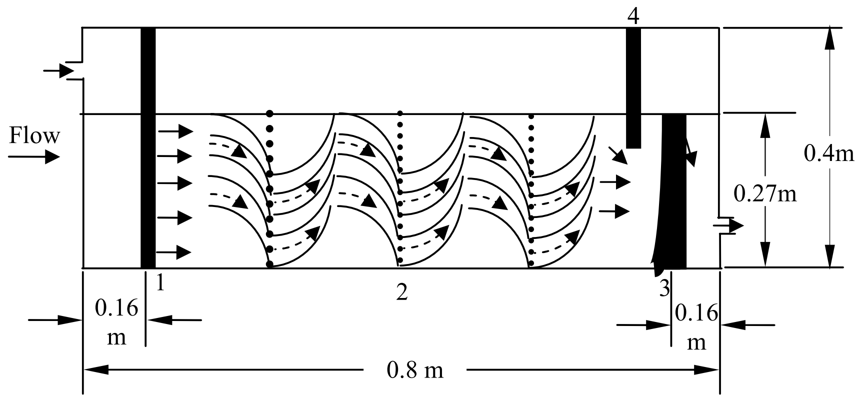
Fig. 2. Schematic Diagram of Experimental (1:Mixing tank, 2:Separator, A=Influent, B=Effluent)

The oil-water separator (length=0.8m, width=0.4m and height = 0.4m) consists of an inlet zone and baffle (0.16 m in length), the oil-water separation zone consisting of series of inclined parallel arc coalescence plates, and the outlet zone outlet and baffle (0.16m). The inlet and outlet baffles were designed in accordance the American Petroleum Institute (API) manual [13], which consists of a slot baffle at the entry, an oil retention baffle and outlet weir (Fig. 3). The coalescence arc plates embedded in the oil-water separation tank were inclined at an angle θ of 55^o from horizontal. The coalescence plates were constructed using aluminium material. Experiment works were carried out using different plate arc lengths in an attempt to configure and determine the optimum plate lengths at different overflow rates. The design parameters and dimensions of arc coalescence plates are shown in Table 1. The governing equations for computation of arc geometry parameters were listed in Appendix I.

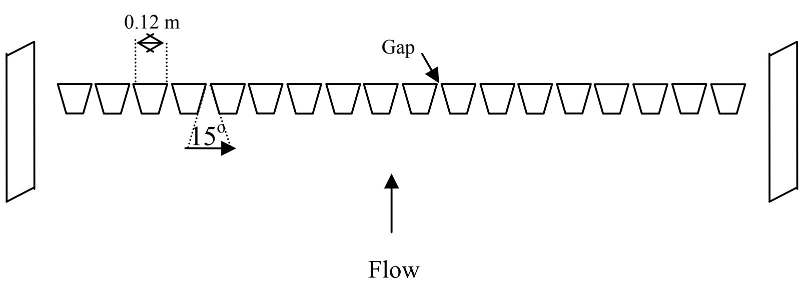
In this experimental work, the ratio of chord length (c) to middle ordinate (m) was c/m = 4 while R=0.57c [10], and the flow rates ranged from $5.6\text{x}10^{-6}$ to 2 $\text{x}10^{-5}$ m^3/s. Additionally, the horizontal projection of the total plate area was correlated with overflow rate with respect to oil removal efficiency. Table 2 shows the number of arc plates versus horizontal projection area for the individual sets of arc length. During the experimental runs, removal efficiencies (E, %) were determined based on Eq. 2.

$$\text{E (\%)} = \frac{C_i - C_o}{C_i} \qquad (2)$$

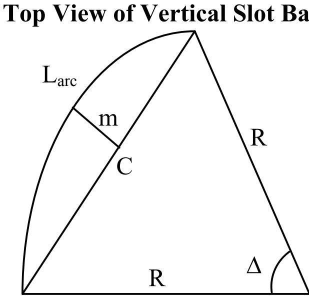
where C_i and C_o are oil droplet concentrations in the water samples collected at inlet (A) and outlet (B) (Fig. 1). The values of v_o/v_r ratio (υ) were correlated with the relative length L_{rel}, i.e. ratio of plate length-to-plate spacing (Table 2). In this experimental work, the plate spacing was theoretically determined to be most appropriate at 50 mm, ratio v_o/v_r (r) was in the range of 0.6 and 3, design ratio at 0.8, and the relative lengths were between 1.7 and 4.4. The horizontal projection area would be the arc plate area multiplied by cosine θ, and this area was used for all cases to determine the effects of arc plate geometries on oil droplet removal efficiencies.



(a) Inlet & Outlet Designs (1-Vertical Slot Baffle, 2-Plate Pack, 3-Effluent Weir, 4-Oil Retention Baffle)



(b) Top View of Vertical Slot Baffle.



(c) Details of Arc Coalescence Plate.

Fig. 3. Oil Water Separator.

Table 1. Design Parameters of Arc Coalescence Plate.

No.	Arc length, m	Arc radius, m	Long chord (c), m	Middle ordinate, (M) m	Central angle (Δ) ^{o}
1	0.85	0.04	0.07	0.0175	122.6
2	0.098	0.0456	0.08	0.02	122.6
3	0.12	0.057	0.1	0.025	122.6
4	0.146	0.0684	0.12	0.03	122.
5	0.17	0.0798	0.14	0.035	122.6
6	0.19	0.0912	0.16	0.04	122.
7	0.22	0.1026	0.18	0.045	122.6

4. Results and Discussion

Experimentally gathered data are presented in Table 3, and Figure 3 illustrates the variations in removal efficiencies, E (%) with respect to different plate relative lengths ($L_{rel.}$). It was demonstrated that the oil droplet removal efficiencies with respect to the ratio of v_0/v_r appeared to be nonlinear, and could be expressed in the form of a second degree polynomial equations, whereby the parameters were dependant on the relative length ($L_{rel.}$). An equation representing second degree polynomial for a given L_{rel} can be written as follow.

$$E(L_{rel.}) = a(L_{rel.})r^2 + b(L_{rel.})r + c(L_{rel.}) \quad (3)$$

where as $a(L_{rel.})$, $b(L_{rel.})$ and $c(L_{rel.})$ are the model parameters. These parameters were calculated or estimated based on the available experimental data with respect to the individual coalescence plate arc lengths (Table 2). To determine model parameter values, a two-stage analysis were carried out. First stage focused on the formulation of a set of E-r relationship holding relative plate lengths as constant, while the second stage involved the simplification or reduction of the complex equation to a simple E-r relationship equation. The analysis on the observed data for the individual plate arc lengths resulted in the formulation of the following equations.

$$E(1.7) = 1.6r^2 + 13.3r - 87.4 \quad (4)$$

Table 2. Arrangement of Arc Coalescence Plates

Arc Length m	Plates No.	Plate Area m^2	Horizontal projection Area m^2
0.85	40	2.04	1.17
0.098	52	2.04	1.17
0.12	43	2.06	1.18
0.146	35	2.04	1.17
0.17	30	2.04	1.17
0.19	27	2.05	1.17
0.22	23	2.02	1.16

$$E(1.96) = 6r^2 + 0.54r - 81.3 \quad (5)$$

$$E(2.4) = 4.9r^2 + 0.7r - 80.6 \quad (6)$$

$$E(2.92) = 4.4r^2 + 1.1r - 82.4 \quad (7)$$

$$E(3.4) = 1.8r^2 + 10.4r - 88.8 \quad (8)$$

$$E(3.8) = 3r^2 + 14.3r - 89.5 \quad (9)$$

$$E(4.4) = 6r^2 + 6.8r - 83.1 \quad (10)$$

From these equations, it was demonstrated that coefficients of r and r^2 could all result in negative values, which indicated that it was not possible to attain 100% removal efficiency. It was also noted that non-linearity could play a dominant role in determining the level of efficiency, especially at higher r values, i.e. when r is greater than 2. Model coefficients shown in Table 4 are plotted in Figure 4 with respect to $a(L_{rel.})$ and $b(L_{rel.})$ or variation of a and b coefficients with $L_{rel.}$, and in Fig. 5 with respect to $c(L_{rel.})$ or variation of c coefficients versus L_{rel}. From the plots (Figs. 4 and 5), it was found that the parameters tended to change in accordance to a third-degree polynomial with respect to L_{rel}.

Table 3. Experimental Removal Efficiency (E) versus *r*.

	Relative Length													
	1.7		1.96		2.4		2.92		3.4		3.8		4.4	
Run	*r*	E	*r*	E	*r*	E	*r*	E	*r*	E	*r*	E	*r*	E
1	0.6	78	0.6	79	0.6	78	0.6	80	0.6	80	0.6	80	0.6	76
2	1	74	1	75	1	75	1	77	1	79	1	72	1	72
3	1.4	65	1.4	68	1.4	71	1.4	73	1.4	73	1.4	64	1.4	63
4	1.8	57	1.8	61	1.8	63	1.8	65	1.8	63	1.8	53	1.8	51
5	2.2	47	2.2	51	2.2	54	2.2	60	2.2	56	2.2	44	2.2	39
6	2.6	49	2.6	40	2.6	45	2.6	49	2.6	49	2.6	32	2.6	26
7	3	30	3	25	3	34	3	40	3	43	3	19	3	10

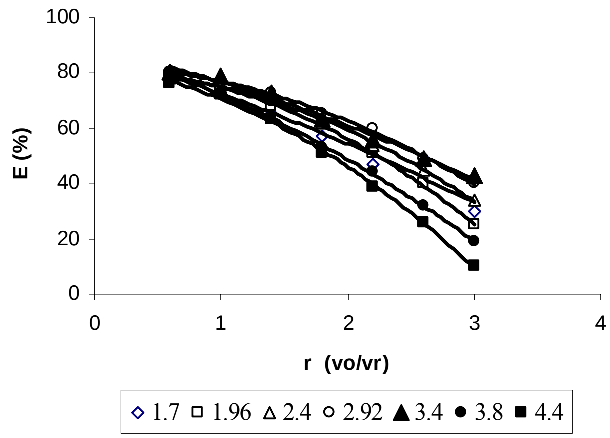


Fig. 4. Removal Efficiency (E, %) versus Relative Lengths (L_{rel}).

Table 4. Second Degree Polynomials: Coefficients a, b & c.

$L_{rel.}$	a	b	c
1.7	-1.6	-13.3	87.4
1.96	-6	-0.54	81.3
2.4	-4.9	-0.7	80.6
2.92	-4.4	-1.1	82.4
3.4	-1.8	-10.4	88.8
3.8	-3	-14.3	89.5
4.4	-6	-6.8	83.1

The relationships of the three parameters and relative plate arc lengths ($L_{rel..}$) are illustrated in the following equations (Eqs. 11, 12, 13 and 14):

$$a(L_{rel.}) = -2.9622L_{rel.}^3 + 26.799L_{rel.}^2 - 76.848L_{rel.} + 63.392 \quad (11)$$

$$b(L_{rel.}) = 9.9771L_{rel.}^3 - 93.983L_{rel.}^2 + 278.68L_{rel.} - 263.41 \quad (12)$$

$$c(L_{rel.}) = -6.5883L_{rel.}^3 + 60.533L_{rel.}^2 - 174.89L_{rel.} + 241.86 \quad (13)$$

Substitute Eqs. 11, 12, and 13 into Equation 3 leads to the following expression:

$$E(L_{rel}) = \left(-2.962L_{rel}^{3} + 26.799L_{rel}^{2} - 76.848L + 65.392\right)r^{2}$$
$$+\left(9.9771L_{rel}^{3} - 93.983L_{rel}^{2} + 278.68L_{rel} - 263.41\right)r \qquad (14)$$
$$-6.5883L_{rel}^{3} + 60.533L_{rel}^{2} - 174.89L + 341.86$$

where L_{rel} is the relative plate length and Eq. 14 is valid for L_{rel} values ranging from 1.7 to 4.4 and r represents v_o/v_r ratio. The experimentally observed and theoretically calculated values with respect to removal efficiencies of oil droplets from wastewaters by using Equation 14 are given in Table 5 for r value equals to 2.

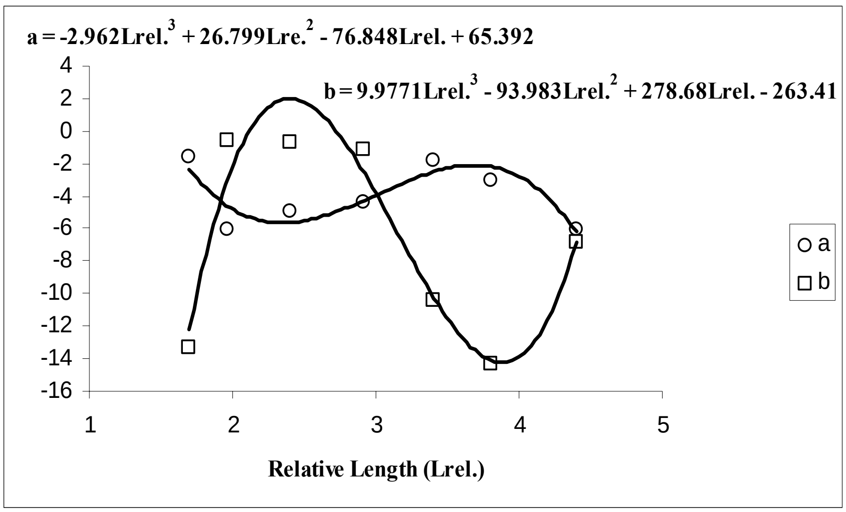


Fig. 5. Variations of a and b coefficients with L_{rel} .

As shown in Table 5, the estimated or predicted removal efficiency values obtained based on general equations showed good agreement with measured or experimental data. The average relative error percentage falls far below the practically acceptable limit of 5%. Based on the relationship between the removal efficiency, E (%) and the plate relative lengths ($L_{rel.}$), the optimum plate length that would result in highest removal efficiency of oil droplets from wastewater can be determined from different *r* values. Plots of removal efficiencies versus relative plate lengths ($L_{rel.}$) are illustrated in Figure 6, whereby the optimum relative plate length that provided the highest removal efficiency was approximately 2.92. It was demonstrated that relative plate lengths would have a significant effect on removal efficiency at higher *r* (v_o/v_r) values, and that at low *r* values, the effect of plate relative plate length on removal efficiency was relatively less significant.

5. Conclusions

In this study, it was concluded that 1) in a gravity-based phase oil-water separator by using the equally spaced inclined multiple parallel arc coalescence plates, oil droplets removal efficiency, E (%) can be expressed as a function of relative plate lengths ($L_{rel.}$) and the *r* value in the following expression.

$$E(L_{rel.}) = \left(-2.962L_{rel.}^3 + 26.799L_{rel.}^2 - 76.848L + 65.392\right)r^2$$
$$+\left(9.9771L_{rel.}^3 - 93.983L_{rel.}^2 + 278.68L_{rel.} - 263.41\right)r$$
$$-6.5883L_{rel.}^3 + 60.533L_{rel.}^2 - 174.89L + 341.86$$

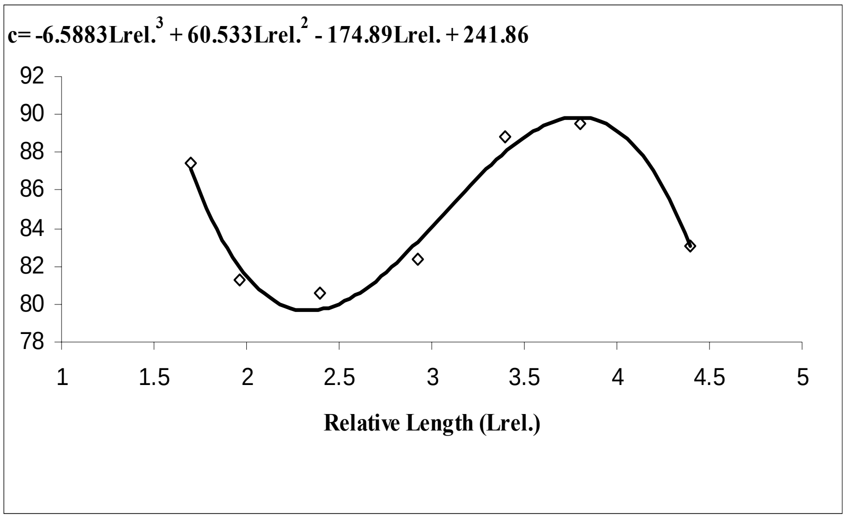


Fig. 6. Coefficient, c versus Relative Arc Length, $L_{rel.}$

Table 5. Removal Efficiencies: Observed versus Predicted.

$L_{rel.}$	Calculated E (%)	Experimental E (%) values	Average error (9%)
1.7	53	52.6	0.75
1.96	57.6	58.4	1.4
2.4	61	60.5	0.82
2.92	61.4	60.8	0.9
3.4	58	56	3.4
3.8	53.5	67.2	20.4
4.4	45	43	4.4
			= 4.6

The above equation can be rewritten to yield;

$$E(L_{rel.}) = (241.86 - 263.4r + 65.392r^2) + (-174.89 + 278.68r - 76.848r^2)L_{rel.} + (60.533 - 93.983r + 26.799r^2)L^2 + (-6.5883 + 9.9771r - 2.962r^2)L^3$$

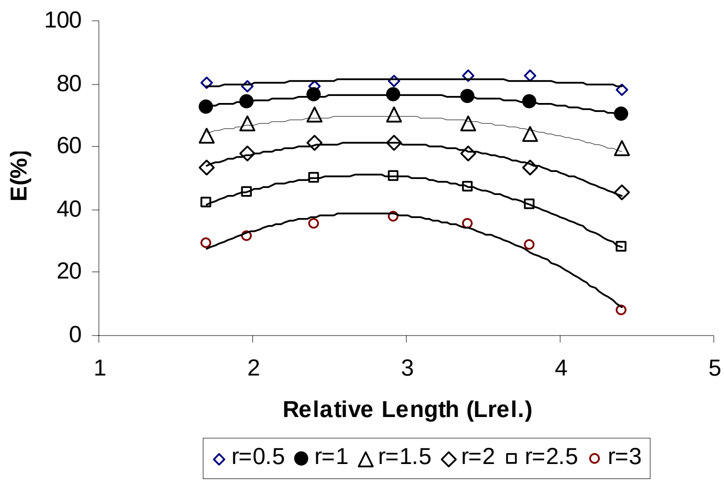


Fig. 7. Observed Removal Efficiencies for Various Relative Lengths (L_{rel})

For optimum (most efficient) removal of oil droplets from wastewaters for a given overflow rate, the derivative of the above expression can be used with respect to L_{rel} that results in the following expression.

$$(-174.89 + 278.68r - 76.848r^2) + (121.066 - 187.966r + 53.598r^2)L_{rel.} + (-19.7649 + 29.9313r - 8.886r^2)L^2_{rel.}$$

It is possible to determine the relative plate length with a given r from this equation. For example, if r equals to 3, then

$$9.945L^2_{rel.} - 39.55L_{rel} + 30.482 = 0$$

This is based on the fact that both r=v_0/v_r and $L_{rel.}$=$L_{arc.}/s$, L_{rel} are estimated to be 2.92. In this study, it was concluded that the optimum arc plate length for this specific oil-water separator was estimated to be 140 mm at an overflow rate of approximately 1.8×10^{-5} m/sec and plates spacing of 50 mm. It was also concluded that arc lengths would have a more significant effect on oil removal efficiency at high overflow rates than at low overflow rate, and the oil removal efficiency was strongly correlated to system's overflow rate and horizontal projection plate area.

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Appendix I

The arc length, chord, and middle ordinate were calculated based using the following equations:

$$L = \frac{2\pi R\Delta}{360}$$

$$C = 2R\sin\left(\frac{\Delta}{2}\right)$$

$$m = R\left(1 - \cos\left(\frac{\Delta}{2}\right)\right)$$