DEVELOPMENT AND PERFORMANCE TESTS OF A SEPARATOR FOR REMOVAL OF PHYSICALLY EMULSIFIED AND FREE OILS FROM WASTEWATERS

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ABSTRACT

A novel oil-water separator with multiple angles parallel coalescence frustums for removal of physically emulsified and free oils from wastewater was recently developed. Performance tests had been carried out to determine its removal efficiency. The primary component of the separator includes a series of inverted and upright frustums-shaped coalescence plates to form a multiple angle plate arrangement for enhance gravity separation and coalescence of oil droplets. The oil removal efficiency (E) of this separator was found to be inversely proportional to influent flowrate (Q) and directly proportional to retention time, t. The efficiency (E) of this separator can be expressed as a function of flowrate (Q), retention time (t), and influent oil concentration (C_{oil}) by a series of power equations; $E = 59.689Q^{-0.107}$ for C_{oil} = 100 mg/L, $E = 70.753Q^{-0.1269}$ for C_{oil} = 1000 mg/L, and $E = 40.16t^{0.127}$ for C_{oil} = 1000 mg/L. For C_{oil} = 100 mg/L, E could be best expressed by polynomial equation, i.e., $E = 0.0001t^2 + 0.0045t + 57.147$. The highest achievable oil-water separation efficiency of this separation system was approximately 82.4% at a flowrate (Q) of $\leq 5x10^{-6}$ $m^{3/s}$, and retention time of $\geq$ 4.80 hours. It was found that the presence of an outlet baffle component for the separator could improve oil removal efficiency by approximately 12.9% as compared to without an outlet baffle.

Keywords: *Coalescence Frustums, Emulsified and Free Oils, Oil-water Separation, Removal Efficiencies*

1. INTRODUCTION

At present, the simplest systems are often inadequate and more complicated systems are either too expensive or too maintenance-intensive [1]. Some of the common separators in use with various designs include 1) American Petroleum Institute (API) Separators, 2) Coalescing plate separators, 3) Coalescing tube separators, and 4) Packing type separators. Burns and Mohr [2] used a coalescing plate separator to treat coolant contaminated with tramp oil. Foley et al. [3] upgraded a refinery "once-through" cooling water systems from a gravity separator with 8 pits arranged in 2 trains with the additional of multiple-angle coalescing plate module. Saleh and Hamoda [4] upgraded of a conventional rectangular sedimentation tanks by applying inclined plate settlers in secondary sedimentation to improve its performance. Veenstra et al. [5] provided an overview of oil-water separation as used in the petroleum refining industries. The two API separators were converted into four cells by adding multiple angle coalescing media pack, divider walls and additional inlet/outlet piping. Schlegel and Stein [6] proposed to feed the sludge/water mixture directly into the sludge layer on the bottom of the secondary sedimentation tanks. Demír [7] carried out a study to determine the settling efficiency and optimum plate angle for a rectangular settling tank with inclined parallel plate.

1A. OBJECTIVES

The objectives of this research project includes (a) to develop an enhanced oil-water separation system with multiple angles of parallel coalescence frustums for removal of physically emulsified and free oils from water suitable for small to medium volume of municipal wastewater loaded with oil and grease, and (b) evaluate and determine the separation system oil removal efficiency, *E* in relation to the specific design and influent parameters such as oil concentrations, flowrates and retention time.

2. HYPOTHESIS

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 and co-workers developed a theoretical basis, but the general concept is not difficult to grasp [8]. As illustrated in Figure 1, when the settler is inclined, the falling particles and the rising liquid get out of each other's way. In 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. 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

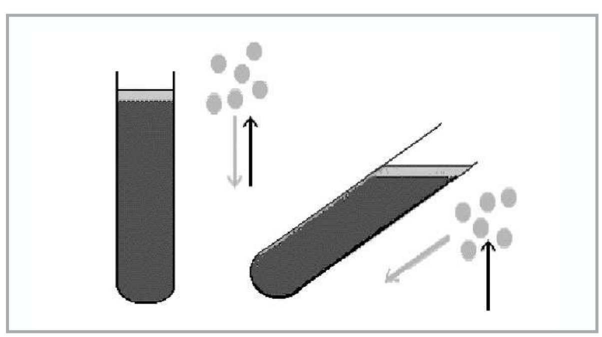

Figure 1: Comparison of particle settling in a vertical tube and an inclined tube

distance to escape from them. This phenomenon is good to enhance separation and therefore inclined medium is recommended.

Generally, the mechanisms of oil droplets gravity separation include the principles of Stokes' Law [9] and Boycott effect [8]. Separation of oil from water is a liquid-liquid separation carried out almost exclusively by gravity separation using flotation of the oil droplets to remove it from water, either natural or enhanced. Natural gravitational separation is carried out in American Petroleum Institute (API) separators and in large tanks [10]. Enhanced gravitational separation is accomplished with centrifugal units, air floatation and flocculation units, and in various type of coalescing plate separators [2].

Oil in water is characterized 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, v_r of the oil droplets. Droplets rise velocity, v_r is given by Stokes' Law [9]:

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

where:
- v_r = rising velocity of the oil droplet size that is 100% removed, m/s
- g = acceleration due to gravity, m/s^2
- μ = dynamic viscosity of continuous liquid, Pa.s
- ρ_o = mass density of the oil droplet, kg/m^3
- ρ = mass density of continuous liquid, kg/m^3
- d = diameter of oil droplet, m

The rise velocity of the oil droplets represents the overflow rate, v_o of the separation tank and is expressed as flowrate per unit area [11]. The overflow rate, v_o is then used to calculate the required plan area, A_p given in the equation below:

$$v_r = \frac{Q}{A_p} = \textit{overflow rate}, v_o \tag{2}$$

Sufficient volume should be provided to allow the oil droplets entering the separator to rise to the surface (to be captured) before the water carrying the droplets exits the opposite end of the separator. The retention time, t is equal to the volume of the separation tank, V divided by flowrate, Q given in the equation below.

$$t = \frac{V}{Q} \tag{3}$$

3. SEPARATOR DEVELOPMENT

In this research, a centre-feed upflow circular tank separation technique was proposed to enable wastewaters loaded with physically emulsified and free oils to flow into the system and allow the horizontal velocity, v_h to decelerate with distance from the inlet, as a result of continual increase of surface area. The reduction in horizontal velocity, v_h would enhance the rising rate for most oil droplets. At the same time, the presence of coalescing frustums promotes optimum oil-liquid separation by providing the inclined medium for Boycott's effect to take place. As illustrated in Figure 1 fluid elements in the inclined tube escape quicker from the oil droplets and flow more easily. Furthermore, as the oil droplets suspension gets more concentrated it also gets denser. This provides more driving force for rising. The net effect is that the oil droplets coalesce and slide up along the plate while liquid flows downward with less interference than in the vertical medium. The tiny or small oil and grease droplets would coalesce and form bigger droplets as they slide along the bottom side of the frustum. Eventually the oil droplets would float to the surface. Thus, the separation of oil and grease from wastewater could be achieved.

The proposed separation technique is very much dependent on the arrangement and orientation of the coalescence frustums, the frustum spacing and the total surface area of the frustums. However, other factors such as influent concentration, flowrates, viscosity and specific gravity, rising properties, volumes of the systems, temperature, and fluid pH are undoubtedly playing important roles in removal or separation efficiency of oil and grease from wastewater. The features of the proposed separator as shown in Figure 2 consist of:

a. Circular separation tank to take advantage of the continual decrease in horizontal velocity,
b. Perforated pipe center-feed (upflow) inlet with inlet well,
c. Parallel coalescence frustum, and
d. Outlet baffle, periphery overflow outlet weir channel to give uniform flow removal and outlet launder to direct effluent out of the separator.

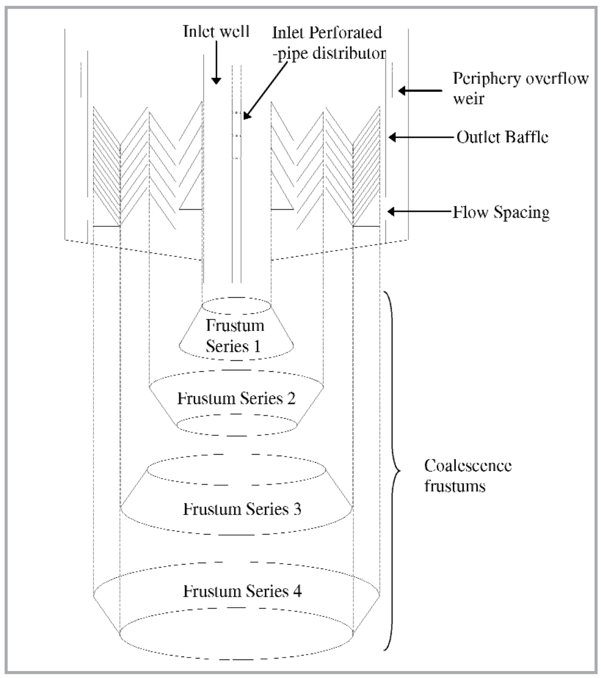

Figure 2: Proposed circular separator with parallel inclined coalescence frustums (consisting of up-right and inverted series of conical frustums)

3A. APPLICABILITY OF COALESCENCE FRUSTUMS

The installation of embedded successive layers of parallel coalescing frustums was expected to serve two purposes, i.e.,

1) to promote laminar flow, and 2) to promote optimum oil-water separation efficiency. By using the principles of a) a maximum amount of frustum surface area provided for oil droplets coalescence to take place, and b) a minimum distance (spacing inversely proportionally to distance from inlet) for lighter oil droplets to rise and hit the bottom side of the frustums as shown in Figure 3. The coalescing frustums assist oil droplets to coagulate and float to the surface to be collected.

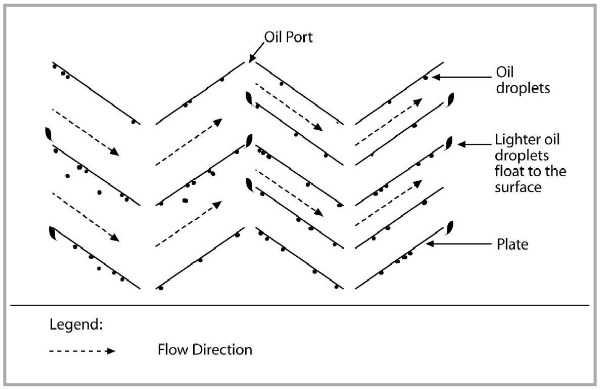

Figure 3: Parallel inclined coalescing frustums: Mechanism of oil-water separation

The use of coalescence frustum facilitates the capture of oil droplets from water, and easy removal of captured oil from the frustums to the surface. Captured oil spreads on the surface of the frustums and coalesces into larger droplets and eventually forms a film of oil on the frustums. It was necessary, having captured the oil on the frustums, to remove it from the frustums in an orderly manner that does not re-entrain the oil into the wastewater stream. The design of coalescence frustums was such that coalesced droplets were required to travel 10 cm (maximum) before they encountered an oil port. These oil ports are vertically aligned so that when the oil droplets are released from the frustums, they rise directly to the surface.

Droplets are released from the frustums when they become large enough that the buoyancy due to their size overcomes the attractive forces holding the droplets onto the frustum. The tendency for the movement of the water horizontally through the frustum packs to "tear off" the droplets from the frustums also exists. The forces holding the droplets and/or film onto the frustums are due to molecular attraction, and are proportional to the area of contact between the oil and the frustum. The force trying to "tear off" the droplets is the frictional force due to the movement of the water. This frictional force is proportional to the surface area of the droplets and the flow velocity of the water.

In conventional inclined plate medium, plates extend from one side of the separator to the opposite side, any and all captured oil must progress along the entire length of the plate before exiting to the surface at the opposite side of the separator. In a large separator, this could be eight (8) feet or more. This means that the amount of oil running along the underside of the plates increases as it moves upward along the sloped under surface of the plates. This gives the flowing water additional opportunities to remove the oil from the plates and carry it downstream, especially if enough oil is captured to partially fill the space between the plates, thus locally increasing the velocity of the water. Even if the oil does not restrict the flow, larger droplets have more tendencies to be removed from the plates. Oil droplets released from the front portion of the packs would probably be captured by subsequent plates, but droplets released in this manner by the downstream end of the packs could exit the separator with the water.

The proposed design provides oil port as illustrated in Figure 3 for the quick release of oil from the frustums in an orderly and systematic manner. Oils float to the surface of the separator instead of being forced to flow additional distances along the frustums before it was released. The sooner the oil floated to the surface the better is its chances of being permanently separated from water. The proposed separator was to be designed as a circular settling basin with parallel coalescence frustums. Settling basin consists of three zones, the inlet, outlet and separation zone. The separation tank was designed to separate all oil droplets sizes of more than 10 µm in diameter with following assumptions:

- Oil droplets rise as discrete particle, free rising,
- Oil droplet shape factor, $\phi = 1$ (spherical),
- Laminar flow, Reynold's Number, $(N_{Re}) < 1$ [12],
- Separation basin is an ideal circular separation system with center-feed flow, and
- Steady-state with even distribution of flow entering and leaving the tank

3B. PERFORATED-PIPE DISTRIBUTOR INLET

Design of separation tank inlet velocity would be maintained <1.0 m/s as recommended by Corbitt, [12] so as not to produce excessive inlet energy. Inlet pipe of the proposed system was designed as a perforated-pipe or sparger based on the module designed by Perry and Green [9] to achieve uniform fluid distribution. For the separation tank, the inlet pipe is a vertical pipe with proposed design of 12 holes of uniform diameter, positioned at 3 levels, 4 holes at each level to direct flow towards coalescence frustums at 4 different directions, i.e., at 0°, 90°, 180° and 270° as shown in Figure 4.

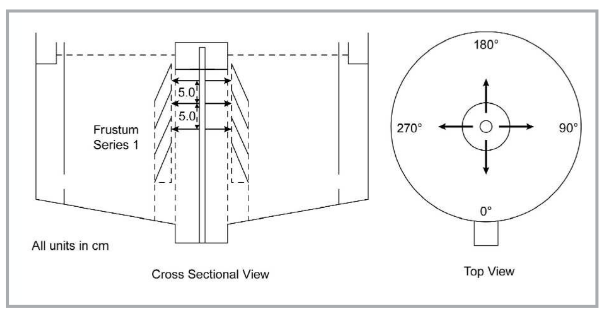

Figure 4: Separation tank inlet pipe design

3C. INCLINED PARALLEL COALESCING FRUSTUMS

In order to achieve desired oil droplet size separation of 10 µm in diameter, plan area for coalescing are to be determined. The rising velocity, v_r required to separate oil droplets size of diameter 10 µm is determined from Equation 1 and the subsequent plan area at different flowrate required for coalescence is determined from Equation 2 and stipulated in Table 1. Flowrate of 1 x 10^{-5} m^3/s gives a reasonable plan area, A_p (=2.09 m^2) for fabrication and therefore was chosen as the inlet flowrate, Q.

Table 1: Amount of planarea, A_p required for various flowrates, Q

Flowrate, Q (m^3/s)	$5x10^{-5}$	$2x10^{-5}$	$1x10^{-5}$	$5x10^{-6}$
Plan Area, $A_p = \frac{Q}{V}$ (m^2)	10.43	4.17	2.09	1.04

Coalescing Frustums Design Criteria

a. Four series of parallel inclined frustums,
b. All series consist of several parallel successive layer of frustums,
c. Series of frustums are placed up-right and inverted positions that subsequently form a multiple-angle arrangement,
d. Frustums are inclined at an angle, θ between 50° to 60°,
e. All frustums have an inclined length, *S* of 10.0 cm,
f. Number of frustums, n would increase with each subsequent series, and
g. Interval between frustums, *l* decreases with each subsequent series.

The inlet well diameter would be 0.2 of basin diameter, *D* [11]. For design purposes, the inlet well diameter was chosen at 14.5 cm for preliminary design and would be reconfirmed by calculations. With inlet well diameter at 14.5 cm, the series of frustums' inner diameters, D_i can be assigned accordingly. Demir [7] experimental results obtained under different surface loadings and plate angles were statistically evaluated and the plate angle providing maximum settling efficiency was determined to be approximately 50° from horizontal. Therefore frustums were design to incline at an angle between 50° to 60° from horizontal. Thus, frustum's outer diameter, D_o and plan area, A_p could be calculated using $D_o = D_i + 2\,(S \cos \theta)$ and $A_p = \pi \left(\frac{D_o^2 - D_i^2}{4} \right)$ (as shown in Figure 5). Intervals between successive frustums, *l* decrease with each subsequent series of frustums, and the first frustum interval has to take into account the perforated-pipe hole interval as shown in Figure 4. The perforated-pipe inlet holes are arranged and adjusted accordingly so as to direct flow towards the openings between frustums. The subsequent series of frustum interval is as listed in Table 2, and the total interval length, l_t for each series should be adequate for the incoming volume of flowrate. Therefore, the total interval length, l_t for all the frustums of each series of frustums would increase with subsequent series of frustums.

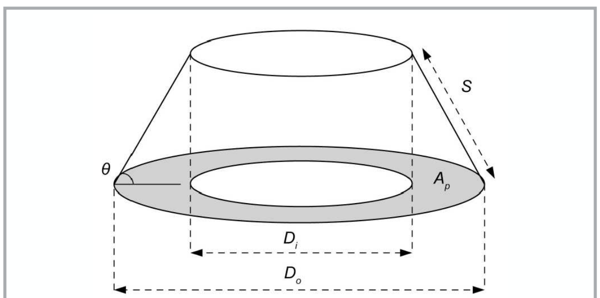

Figure 5: Coalescence frustum design details and parameters

Table 2 indicates that coalescence frustum arrangement that provides a total plan area, A_p of 2.07 m^2, which is adequate to met the required 2.09 m^3 for separator design flowrate, *Q* of $1x10^{-5}$ m/s as shown in Table 1. Theoretically, oil droplets that can be separated or removed with the design arrangement of coalescence frustums can be obtained with known g, μ, ρ_o and ρ.

Table 2: : 1st to 4th series of frustum characteristics and design

	Series 1	Series 2	Series 3	Series 4
Orientation	 Up-right	 Inverted	 Up-right	 Inverted
Angle, θ (°)	60	55	55	55
Inclined length, *S* (cm)	10.0	10.0	10.0	10.0
Inner Diameter, D_i (cm)	15.0	26.5	39.0	50.5
Outer Diameter, D_o (cm)	25.0	37.5	50.0	61.5
$D_o - D_i$ (cm)	10.0	11.0	11.0	11.0
Plan Area, A_p (m^2)	0.0314	0.0553	0.0769	0.0968
Number of frustum, n	4	6	8	13
Total A_p per series (m^2)	0.0943	0.2766	0.5385	1.1616
Total A_p (m^2)				2.0710
Interval, *l* (cm)	5.0	3.5	2.5	1.5
Total interval length, lt (cm)	15.0	17.5	17.5	18.0

3D. SEPARATOR SIZING, OUTLET BAFFLE AND OVERFLOW WEIR DESIGNS

The outlet baffle is a layer surrounding the 4 series of frustum to prevent oil droplets from washout or escaping into the effluent. Therefore, the outlet baffle diameter, D_b was chosen as 65 cm. The outlet baffle consists of 2 sections; the top layer and the bottom layer. The bottom layer is placed at the bottom of the tank and its height is 5 cm to collect and prevent sludge (if any) from being washed out as effluent. The top layer has a height of 32 cm and is positioned 5 cm above the bottom layer. The intention of this 5 cm spacing is to provide flow passage for effluent to the outlet overflow weir as illustrated in Figure 2 and Figure 6. An additional 5 cm flow channel outside the outlet baffle is designated for the overflow weir. The total basin diameter is therefore 75 cm.

In this case, the inlet well diameter would be 0.2 of basin diameter [11], i.e., the outlet baffle diameter, D_b (65 cm). Therefore, it gives a 13 cm (0.2 x 65 cm) inlet well diameter. The bottom of the tank consists of an inverted cone that slopes to the center at an angle of 8.5° so as to promote collection of sludge, if present. The outlet overflow weir is a periphery v-notch weir channel to give an uniform flow removal and outlet launder collect and direct effluent out of the separator. The design parameters are shown in detail in Figure 7. The overflow weir is positioned at 31 cm above the basin. This gives a water depth of 26 cm inside the outlet baffle. High level of water above the series of frustums would be included to provide space for the installation of an oil weir or skimming device for removal of separated oil in the future. Thus, the outlet baffle would only trap oil as a layer on the water surface without being removed from the system.

In this design, the bottom cone, 5 cm bottom layer of the outlet baffle and 5 cm flow passage of the outlet baffle is not

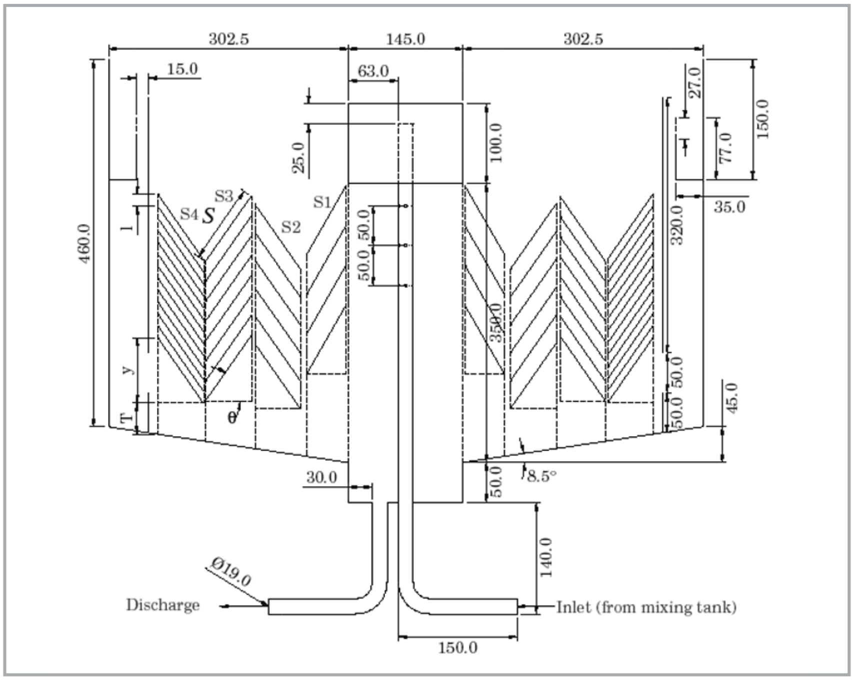

Figure 6: Separation system design details and parameters

considered in the design volume and it is taken as being the circular tank areas multiply by the depth of the water at the sides of the tank. Therefore, tank sizing design considers the outlet baffle diameter, D_b of 65 cm and the water level of 26 cm, which gives the tank volume, V as 86 liters. The required retention times for various flowrates are calculated using Equation 3 and presented in Table 3. Figure 6 shows the design diagram of the separation tank and its design details and parameters. Table 4 is a summary of the separation tank design details and parameters.

Table 3: Required retention times, t for various flowrates, Q

Flowrate, Q (m^3/s)	$2.0x10^{-5}$	$1.0x10^{-5}$	$0.7x10^{-5}$	$0.5x10^{-6}$
Retention time, t (min)	72	144	205	288

4. EXPERIMENTAL PROCEDURE

4A. MIXING TANK SET UP AND SAMPLE PREPARATION

The primary function of the mixing tank in this experimental setup was to mix oil with water to form water and physically emulsified and free oils solution with known concentrations, and to pump the mixture at designed flowrate as influent to the separation system. The mixing tank was designed as a typical agitation process vessel or a cylindrical vessel with a vertical axis at a capacity of 200 litres (L). The mixing tank is intended as a rapid mixing tank using mechanical agitators to impart power to the water to produce high shear, turbulence and velocity gradient (G). The mixing tank was designed and made from fibreglass material. This mixing tank has a submersible pump at the bottom of the tank and a single impeller shaft system installed with a 0.25 HP motor as shown in Figure 8.

A volume of 200 litres of oil water mixture at known concentrations were prepared with palm olein oil with mass density, ρ_o given as 890 kg/m^3. Mixing tank was filled with 200 L of water and oil as illustrated in Table 5, and the water and oil was mixed for 5 minutes by switching on the motor-impeller system. A schematic diagram of the separation system and mixing tank connected in series is illustrated in Figure 9.

4B. SEPARATOR'S OUTLET BAFFLE CONFIGURATION

Different outlet baffle configuration would have different effect intensities on the overall separation tank efficiency. In this research work, a total of three (3) different outlet baffle configurations were tested consisting of (a) 5 cm flow spacing provided between top and bottom layers of outlet baffle, (b) top layer of outlet baffle above water level while a 5 cm flow spacing provided above tank bottom, and (c) without an outlet baffle. Oil concentration in water would be measured using an oil water analyser, Model OCMA-310 of HORIBA [13].

HORIBA oil content analyser deploys infrared absorption method to measure oil content in water [13]. Oil dispersed in water is extracted (dissolved) in solvent i.e., $Cl(CF_2\text{-}CFCl)_2Cl$. The oil concentration in the sample was measured from the changes in the amount of infrared absorption in the 3.4 to 3.5 µm wavelength range of the extracted liquid. The OCMA-310 is a non-dispersive infrared analysis meters which allow a more sensitive

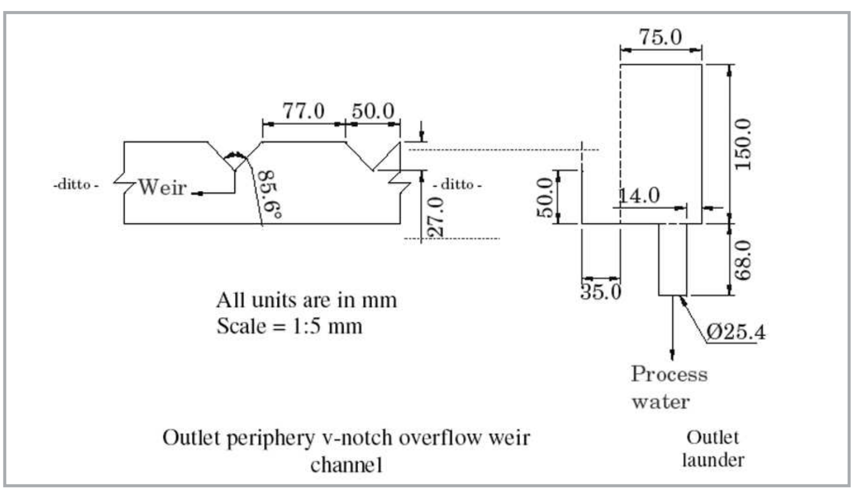

Figure 7: Outlet periphery v-notch overflow weir channel and outlet launder design

Table 4: Summary of separation system design details and parameters

Description	Unit	Parameter			
Volume	L	86			
Design flowrate, Q	m^3/s	1×10^{-5}			
Overflow rate, v_o	m/s	4.796×10^{-6}			
Retention time, t	min	144			
Inlet					
Perforated-pipe distributor to direct flow to the interval of coalescence frustum and provide an uniform distribution of flow.					
Number of hole	-	12, 4 at 3 level			
Hole interval	m	0.05			
Hole diameter, d_{hole}	mm	3.30			
Inlet well diameter	m	0.145			
Coalescence frustum					
Parallel inclined coalescence frustum in the form of conical frustum					
		Series 1	**Series 2**	**Series 3**	**Series 4**
Position		Up-right	Inverted	Up-right	Inverted
Angle	°	60	55	55	55
Inclined length, S	m	0.10	0.10	0.10	0.10
Inner diameter, D_i	m	0.15	0.265	0.39	0.505
Outer diameter, D_o	m	0.25	0.375	0.50	0.615
Interval, l	m	0.05	0.035	0.025	0.015
Number of frustum, n		4	6	8	13
Outlet					
Outlet baffle prevent oil droplets from escaping into the effluent and collect separated oil.					
Outlet baffle 5 cm flow spacing direct effluent out at the bottom of the tank.					
Periphery outlet v-notch overflow weir to give uniform removal.					
Outlet launders collect and direct effluent out of separator tank.					
Baffle diameter, D_b	m	0.65			
Flow spacing	m	0.05			
Top baffle height	m	0.32			
Bottom baffle height	m	0.05			
Weir v-notch angle	°	85.6			
Distance between weir	m	0.127			

analysis which required less sample because cell length can be made shorter and its has the ability to take measurements without losing elements with low boiling points [13].

The experiment was carried out with four (4) series of multiple angles inclined parallel coalescence frustums in the separation tank. The outlet baffle was first removed from the separation tank, and an influent oil concentration of 100 mg/L was prepared in the mixing tank (Table 5). A volume of 1.0 L of influent sample was collected from the mixing tank and influent oil concentration was measured with the HORIBA oil water analyzer. The influent was pumped to the separation tank at the flowrate of 1×10^{-5} m^3/s. The mixture from the mixing tank was continuously pumped into the separation tank for a period of 144 minutes (which was also the retention time in the separator) at a flowrate of 1×10^{-5} m^3/s. The mixture in mixing tank was then topped up by addition of 20.0 L of water and 2.25 mL of oil. The mixture was agitated for 2 minutes. A 1.0 L of effluent was collected and effluent oil concentration was measured with the HORIBA oil water analyzer. The procedure was then repeated for outlet baffle configurations with (a) 5 cm flow spacing provided between top and bottom layers of outlet baffle, and (b) top layer of outlet baffle above water level while a 5 cm flow spacing provided above tank bottom.

4C. DETERMINATION OF OIL REMOVAL EFFICIENCIES

Separation tank oil removal efficiency would vary with different influent flowrates (Q), influent oil concentrations (C_{oil}), and separation tank retention times (t). Different influent oil concentrations tested were 100 mg/L and 1000 mg/L, which were 2 and 3 orders of magnitude higher than the desired separator effluent concentration of 10 mg/L. In this research study, a total of eight (8) performance tests were carried out, and the details are illustrated in Table 6.

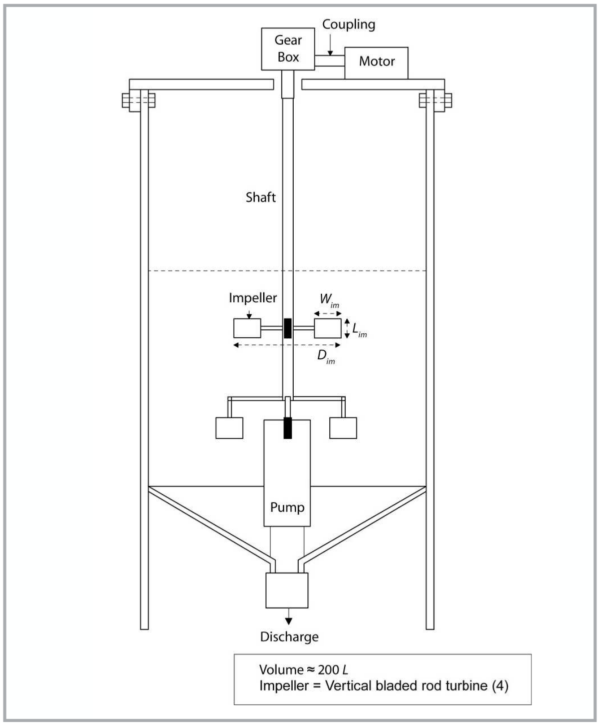

Figure 8: Mixing tank equipped with bladed turbine and submersible pump

The experiment was carried out with four (4) series of coalescence frustums in the separation tank. Influent oil concentration of Test 1 as stated in Table 6 (the sample was prepared based on the details shown in (Table 5). A volume of 1.0 L of influent sample was collected from the mixing tank and influent oil concentration was measured with the HORIBA oil water analyzer. The influent was pumped to the separation tank at 2.0x10^{-5} m^3/s. The mixture from the mixing tank was continuously pumped into the separation tank for a period of 72 minutes.

Table 5: Ratio of water and palm olein oil (ml)

Oil concentration, C_{oil} (mg/L)	Water (L)	Palm Olein Oil (mL)
100	200	22.74
1000	200	224.97

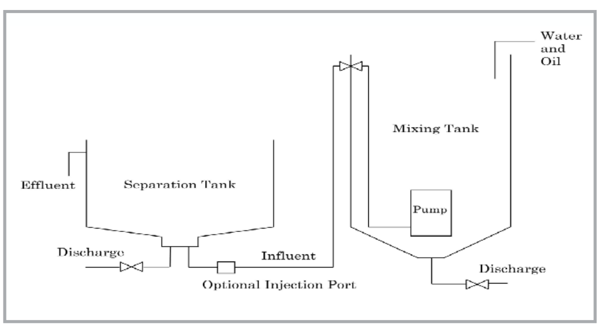

Figure 9: Schematic diagram of mixing and separation system

The mixture in mixing tank was then topped up by addition of 20.0 L of water and 2.25 mL or 22.5 mL of oil to produce an influent oil concentration of 100 mg/L or 1000 mg/L, respectively whenever necessary. The mixture was thoroughly agitated for 2 minutes. A volume of 1.0 L of effluent was collected and measured with the HORIBA oil water analyser. The procedure was then repeated for Test 2 to Test 8 (Table 6).

Table 6: Relationship of influent concentrations, flowrates and retention times

Test	Influent oil concentration (mg/L)	Influent flowrate, Q (m^3/s)	Retention time, t (min)
1	100	2.0 x 10^{-5}	72
2	100	1.0 x 10^{-5}	144
3	100	0.7 x 10^{-5}	205
4	100	0.5 x 10^{-5}	288
5	1000	2.0 x 10^{-5}	72
6	1000	1.0 x 10^{-5}	144
7	1000	0.7 x 10^{-5}	205
8	1000	0.5 x 10^{-5}	288

5. RESULTS AND DISCUSSION
5A. EFFECT OF OUTLET BAFFLE CONFIGURATION ON OIL REMOVAL EFFICIENCY

As shown in Table 7, there was an increase of approximately 12.9% (from 47.5% to 60.4%) when an outlet baffle was installed with a 5 cm flow spacing between the top and bottom layer of outlet baffle. The outlet baffle prevents coagulated oil droplets escaping from the 4th coalescence frustums due to close distance between the 4th coalescence frustums and outlet weir. With the top layer of outlet baffle positioned 5 cm above tank bottom, oil removal efficiency was found to increase by approximately 11.0% (from 47.5 to 58.5) as compared to without outlet baffle. However, when the bottom and top layer of outlet baffle was separated by 5 cm flow spacing, the removal efficiency was approximately 60.4 %.

Table 7: Outlet baffle configuration versus oil removal efficiency

	Without outlet baffle	Top layer of outlet baffle at 5 cm above tank bottom	Bottom and top layer of outlet baffle separated by 5 cm (flow spacing)
Influent oil concentration, mg/L	93.9	104	104
Effluent oil concentration, mg/L	49.3	43.2	41.2
Oil Removal Efficiency, %	47.5	58.5	60.4

5B. OIL REMOVAL EFFICIENCIES AS A FUNCTION OF FLOWRATES AND INITIAL OIL CONCENTRATIONS

Figure 11 illustrates that oil droplets removal efficiencies, E of the system is indirectly proportional to flow rate, Q. For instance, for influent oil concentration of 100 mg/L oil removal efficiencies, E were 70.38%, 60.38% and 57.94% at flow rate, Q 0.5x10^{-5} m^3/s, 1.0x10^{-5} m^3/s and 2.67 x 10^{-5} m^3/s respectively. For influent oil concentration of 1000 mg/L oil removal efficiencies, E were 82.38%, 76.02% and 68.95% at flow rate, Q 0.5x10^{-5} m^3/s, 1.0x10^{-5} m^3/s and 2.0 x 10^{-5} m^3/s respectively.

In Figure 11, it is also illustrated that oil removal efficiencies, E of the separation system are indirectly proportional to retention time, t; oil removal efficiency increases with a decrease in flowrate or an increase in retention time. For instance, for influent oil concentration of 100 mg/L oil removal efficiencies, E were 70.38%, 60.38% and 57.94% at retention time, t 288 minutes, 144 minutes and 55 minutes respectively. For influent oil concentration of 1000 mg/L oil removal efficiencies, E were 82.38%, 76.02% and 68.95% at retention time, t 288 minutes, 144 minutes and 55 minutes respectively. The highest oil removal efficiency, E achieved was approximately 82.38% for influent oil concentration of 1000 mg/L at a flowrate of $0.5\text{x}10^{-5}$ m³/s and retention time of 288 minutes. The detailed experimental data and results are shown in Table 8.

Table 8: Oil removal efficiency, E at different flowrate, Q and retention time, t

Oil concentration, mg/L	Flowrate, Q (m³/s)	Retention time, t (min)	Influent oil concentration, mg/L	Effluent oil concentration, mg/L	Efficiency, E (%)
100	2.67 x 10^{-5}	55	126	53.0	57.94
	2.0 x 10^{-5}	72	104	39.4	62.12
	1.0 x 10^{-5}	144	104	41.2	60.38
	0.7 x 10^{-5}	205	104	36.8	64.62
	0.5 x 10^{-5}	288	104	30.8	70.38
1000	2.0 x 10^{-5}	72	976	303	68.95
	1.0 x 10^{-5}	144	976	234	76.02
	0.7 x 10^{-5}	205	976	208	78.69
	0.5 x 10^{-5}	288	976	172	82.38

In Figures 10 and 11, influent oil concentration of 100 mg/L at a flowrate of $2.0\text{x}10^{-5}$ m³/s (retention time of 72 minutes), the oil removal efficiency was 62.12% and this is higher than the oil removal efficiency (60.38%) at the same influent concentration with lower flowrate of $1.0\text{x}10^{-5}$ m³/s, and doubled the retention time of 144 minutes. It also shown that at an influent oil concentration of 100 mg/L, flowrate of $2.67\text{x}10^{-5}$ m³/s, and retention time of 55 minutes, the oil removal efficiency was approximately 57.94%. Therefore, oil removal efficiency of 62.12% for influent oil concentration of 100 mg/L at flowrate of $2.0\text{x}10^{-5}$ m³/s for retention time of 72 minutes shall be considered erroneous and be excluded.

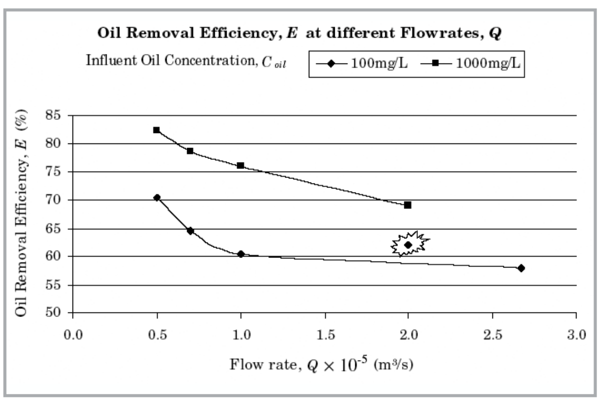

Figure 10: Oil removal efficiency at different flowrate for C_{oil} 100 mg/L and 1000 mg/L

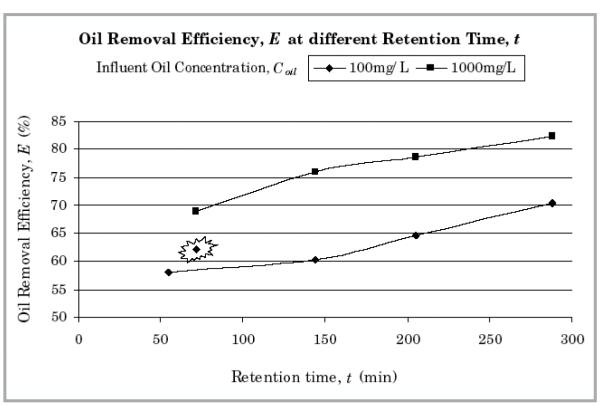

Figure 11: Oil removal efficiency at different retention time for C_{oil} 100 mg/L and 1000 mg/L

Figure 12 shows the plots of polynomial versus power in an attempt to correlate oil removal efficiency, E and flowrates, Q for influent oil concentrations, C_{oil}, of 100 mg/L and 1000 mg/L through curve fitting practice. Table 9 shows the equations of the individual correlationship obtained from the curve fitting practice chosen that were based on the relationship curves deemed as suitable to represent oil removal efficiency versus flowrate. As shown in Figure 12, for C_{oil} of 100 mg/L, oil removal efficiency for the polynomial relationship decreases from 70.38% (at Q = 0.5 x 10^{-5} m³/s) to ≈ 53% (at Q = 1.9 x 10^{-5} m³/s), and E increases from ≈ 53% (at Q = 1.9 x 10^{-5} m³/s) to E = 57.94% (at Q = 2.67 x 10^{-5} m³/s). Theoretically, removal efficiency would decrease with an increase in flowrate, and this could be due to experimental or/and analysis error(s). Thus, as shown in Table 9, even though the relationship of polynomial plot (R^2 = 0.9884) is better than power plot (R^2 = 0.8270), equation $E = 59.689Q^{-0.107}$ (power plot) is deemed as more representative in this case. For C_{oil} of 1000 mg/L, power relation of $E = 70.753Q^{-0.1269}$ is deemed more suitable with R^2 = 0.9958 as compared to polynomial plot R^2 = 0.9943. However the polynomial relation can also be representative due to its high R^2 value.

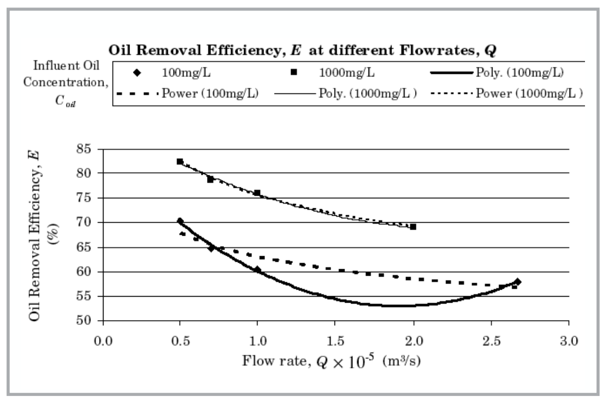

Figure 12: Polynomial and power as a function of oil removal efficiency and flowrates

Table 9: Oil removal efficiencies as a function of flowrates and influent concentrations

Influent oil concentration, C_{oil} mg/L	Relationship	Equation	R^2
100	Polynomial	$E = 23.917Q^2 - 54.659Q + 84.18$	0.9884
	Power	$E = 59.689Q^{-0.107}$	0.8270
1000	Polynomial	$E = 11.056Q^2 - 31.125\,Q + 90.409$	0.9943
	Power	$E = 70.753\,Q^{-0.1269}$	0.9958

Figure 13 shows the plots of polynomial versus power for influent oil concentrations, C_{oil} of 100 mg/L and 1000 mg/L through curve fitting practice. Table 10 shows the equations of each influent oil concentration obtained from the curve fitting practice chosen based on the relation curve deemed as suitable to represent oil removal efficiency versus retention time. For C_{oil} of 100 mg/L, polynomial relation of $E = 0.0001t^2 + 0.0045t + 57.147$ is considered more suitable with R^2 = 0.9956 as

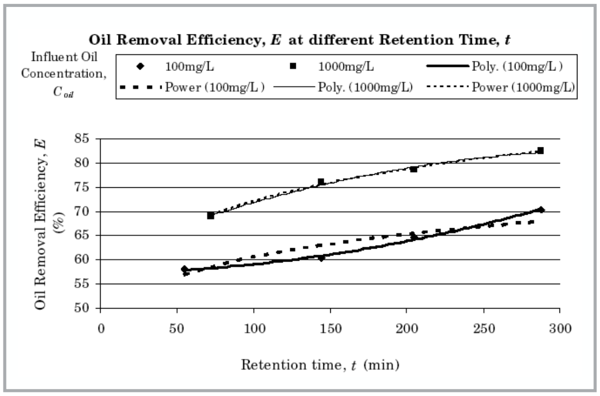

Figure 13: Polynomial and power as a function of oil removal efficiency and retention time, t

Table 10: Oil removal efficiencies versus retention time and influent concentrations

Influent oil concentration, C_{oil} mg/L	Relationship	Equation	R^2
100	Polynomial	$E = 0.0001t^2 + 0.0045t + 57.147$	0.9956
	Power	$E = 36.731t^{0.1086}$	0.8312
1000	Polynomial	$E = -0.0002t^2 + 0.1275t + 60.922$	0.9925
	Power	$E = 40.16t^{0.127}$	0.9960

compared to power plot of $R^2 = 0.8312$. For C_{oil} of 1000 mg/L, power relation of $E = 40.16t^{0.127}$ would be more suitable with $R^2 = 0.9960$ as compared to polynomial plot with $R^2 = 0.9925$. The polynomial relation can also be representative due to its high R^2 value of 0.9925. With these relationships, oil removal efficiencies achievable by the separator could be estimated for different flowrates and retention times.

5C. COMPARISON OF THEORETICALLY CALCULATED AND EXPERIMENTAL RESULTS

The separator system was designed to separate oil droplets sizes of more than 10 µm in diameter to meet effluent requirements (Malaysia Environmental Quality Act and Regulation) of less than 10 mg/L [1]. The theoretically calculated results show that the design and capacity of the current system is capable of achieving oil droplets separation (more than 10 µm in diameter) at influent flow rate at or less than 1.0×10^{-5} m/s.

With reference to the experimental results in Table 8, oil removal efficiency at different flowrates and influent concentrations, the desirable effluent oil concentration of 10 mg/L had not been achieved for all the experimental conditions. However, this does not imply that the separator could not separate oil droplets down to 10 µm in diameter. The possible factor that might have contributed to this occurrence was due to a different influent oil droplets distribution spectrum. In this experiment, the mixing influent oil droplets distribution spectrum had not been determined. The emulsion of oil in water could contain a large portion of its oil in the form of oil droplets with diameter below 10 µm, which the separator was not designed to separate. If a large portion of the oil is in the form of oil droplets of diameter below 10 µm, then theoretically the separator is incapable of separating these oil droplets which result in higher concentration of oil in the effluent which could not meet the regulatory requirement and separator design requirement of 10 mg/L.

6. CONCLUSIONS

At present, circular enhanced gravity separator with inclined coalescing frustum had not been extensively developed and used so far for removing oil and grease from wastewaters. Patent search of a circular phase separation tank with inclined coalescence plate arranges in multiple angle by Intellectual Property Services, SIRIM Berhad, Malaysia confirmed the novelty of such separator [14]. It was found that the highest achievable oil-water separation efficiency by the separator is approximately 82.38% for 1000 mg/L influent oil concentration at flowrate of $<5 \times 10^{-6}$ m^3/s and retention time of >288 minutes. It was concluded that oil removal efficiency, E was inversely proportional to influent flowrate, Q and retention time, t. The correlation of oil removal efficiency and influent flowrate could be represented by $E = 59.689Q^{-0.107}$ for 100 mg/L influent oil concentration, and $E = 70.753Q^{-0.1269}$ for 1000 mg/L influent oil concentration. The correlationship of oil removal efficiency, E and retention time, t could be represented by $E = 0.0001t^2 + 0.0045t + 57.147$ for 100 mg/L influent oil concentration, and $E = 40.16t^{0.127}$ for 1000 mg/L influent oil concentration. It was also concluded that the presence of outlet baffle would enhance the collection of coagulated oil within the tank and this would increase oil removal efficiency by approximately 12.9%. ■

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LIST OF SYMBOLS, DEFINITIONS AND NOTATIONS

μ = dynamic viscosity of continuous liquid, Pa.s
ρ = mass density of continuous liquid, kg/m^3
θ = frustum angle, $^\circ$
ρ° = mass density of the oil droplet, kg/m^3
A_p = plan area, m^2
d = diameter of oil droplet, m
D_b = outlet baffle diameter, m
D_i = inner frustum diameter, cm
D_o = outer frustum diameter, cm
g = acceleration due to gravity, m/s^2
l = interval between frustum, cm
lt = total interval length, cm
n = Number of frustum
N_{Re} = Reynold Number
Q = inlet flowrate, m^3/s
r = radius, m
S = inclined length, cm
t = retention time, s
V = tank volume, m^3
v_h = horizontal velocity, m/s
v_o = overflow rate, m$^{3/s}$
v_r = rising velocity of the oil droplet size that is 100% removed, m/s
C_{oil} = influent oil concentration, mg/L
D_{im} = impeller diameter, m
E = oil removal efficiency, %
G = velocity gradient, s^{-1}
L_{im} = impeller length, m
t = retention time, s
W_{im} = impeller width, m

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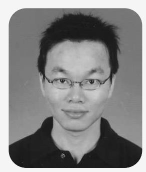

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