Treatment of Oily Wastewater by Fibrous Coalescer Process : Stage Coalescer and Model Prediction

Pisut Painmanakul, Kotchakorn Kongkangwarn, and Nattawin Chawaloesphonsiya

***Abstract*—**The coalescer process is one of the methods for oily water treatment by increasing the oil droplet size in order to enhance the separating velocity and thus effective separation. However, the presence of surfactants in an oily emulsion can limit the obtained mechanisms due to the small oil size related with stabilized emulsion. In this regard, the purpose of this research is to improve the efficiency of the coalescer process for treating the stabilized emulsion. The effects of bed types, bed height, liquid flow rate and stage coalescer (step-bed) on the treatment efficiencies in term of COD values were studied. Note that the treatment efficiency obtained experimentally was estimated by using the COD values and oil droplet size distribution. The study has shown that the plastic media has more effective to attach with oil particles than the stainless one due to their hydrophobic properties. Furthermore, the suitable bed height (3.5 cm) and step bed (3.5 cm with 2 steps) were necessary in order to well obtain the coalescer performance. The application of step bed coalescer process in reactor has provided the higher treatment efficiencies in term of COD removal than those obtained with classical process. The proposed model for predicting the area under curve and thus treatment efficiency, based on the single collector efficiency (η_T) and the attachment efficiency (α), provides relatively a good coincidence between the experimental and predicted values of treatment efficiencies in this study.

***Keywords*—**Stage coalescer, Stabilized emulsions, treatment efficiency, and model prediction

NOMENCLATURE

Δp	Pressure drop in the coalescer column (Pa)
g	Gravity acceleration ($m{\cdot}s^{-2}$)
ψ	Sphericity factor of fiber media (-)
D_E	Diameter of oil droplet (m)
D_P	Diameter of fiber media (m)
ε	Media porosity (-)
H	Media bed height (m)
V_0	Liquid superficial velocity ($m{\cdot}s^{-1}$)
C	Effluent COD in experiment ($mg{\cdot}l^{-1}$)
C_0	Influent COD in experiment ($mg{\cdot}l^{-1}$)
α	Attachment efficiency (-)
η_T	Single collection efficiency (-)
β	Correction factor (-)
σ_D	Surface tension of dispersed phase liquid ($mN{\cdot}m^{-1}$)
σ_C	Surface tension of continuous phase liquid ($mN{\cdot}m^{-1}$)

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I. INTRODUCTION

OIL is one of the important contaminants in water and causes the wastewater problems in environments. In practice, this can form various types of oily wastewaters; for instance, soluble oil in water, emulsion with and without surfactants, or floating film [1]. Especially, an emulsion with surfactants is difficult to handle, since it has very high stability due to the very small oil droplets size presence in wastewater [1]. Normally, different types of oil can be possibly contained in water, like cutting fluids, lubricants, light and heavy hydrocarbons, fats, etc. Moreover, even very low concentrations of oil in the environment, it can be toxic for organisms in water. Therefore, many treatment methods have been proposed for oil removal from water. Separation processes are widely used, such as settlers, floatation, centrifuges, and bed coalescers. Note that the treatment efficiency obtained with each separation methods can be described by Stoke's law: the separating velocities of oil particles from water relate with density difference of two immiscible phases, particle size, gravity force, and liquid viscosity [2]. All of these parameters have been used as a main mechanism in order to develop for high efficiency separation methods.

Coalescer is equipment that is suitable for liquid-liquid dispersion, emulsion separation. An important component of coalescer is the media bed (normally in fiber or granular bed) that can increase the oil particles size and thus the separating velocities from wastewater [2]. Moreover, the mechanisms obtained with this treatment process are stable and usually assumed that concentration of disperse phase is constant along the media bed length [3]. In fact, media selection is an essential point in order to achieve the efficient coalescer performance: the media selected typically are the lipophilic or hydrophobic condition [1]. Because, it can enhance the attachment ability between oil droplets and coalescer media, and thus produce the larger oil particles.

Regarding to the related literatures, many researches have studied the mechanisms of coalescence process within the different coalescer beds [3-4]. From Rebelein and Blass (1990) and Sokolovic et al.)1997) [4, 5], the influence of physical media configurations (bed length, density and porosity of coalescer bed, media size, types of materials for manufacturing coalescer media) and also operating conditions (liquid flow rate, various types of oily wastewater, pressure drop across media bed, reactor dimension) have been taken into account in order to achieve the fine efficiencies and also the suitable design criteria of the coalescer system. Moreover, Wanichkul [6] has analyzed and compared the treatment efficiencies obtained from coalescer process with those obtained from different methods, like Ultrafiltration, Hydrocyclone, Distillation and also the Hybrid processes based on these methods. Concerning to how important of coalescer media selection on treatment efficiencies, Madia et al. (1976) [7] have studied the influence of packing wettability on oil droplet coalescence mechanism. Recently, Bhagat et al. (2006) [8] and Fei et al. (2008) [9] have been proposed the techniques for modifying the hydrophobic condition of coalescer media beds using the silica coatings by the dip coat technique and the ethanol grafted polyacrylonitrile method, respectively. In fact, the investment and operating cost for applying these coating or grafting techniques is still high due to the chemical agents used. The cost of media bed and coalescer system is also the important factor to be considered. Note that, some wastes such as peat, sawdust and chrome shavings have been reused as oil sorbent and coalescer media in order to provide cheaper cost for oily wastewater treatment [10-12]. However, low efficiencies in terms of oily wastewater treatment and its recovery from wastewater, media clogging problems and solid waste generated are the disadvantage obtained generally with the classical coalescer system [1, 13].

To fill this gap, the objective of this research is to study the effect of plastic and stainless materials used as fiber coalescer media, and also to augment the process efficiencies by applying the step-bed coalescer concept, which would benefit from more COD removal obtained. Moreover, this study was applied less expensive fiber, which commonly found in market, to encounter the media cost and searching problems. An oily emulsion with surfactants was interested in this study due to its high stability. Finally, the model for predicting the overall treatment efficiency was proposed by applying the target collision efficiency between coalescer media and different sizes of oil droplets presence in wastewater

II. Experimental Procedure

A. Experimental set-up

The apparatus used in this study is shown in Fig.1, which included a 5 cm diameter and 1 m length column coalescer (1). The fibrous media applied in this experiment, as illustrated in Fig. 2, were stainless (Uni-top trading 1998 co., ltd., BKK, Thailand) and plastic coalescer media (White crane co., ltd., Bkk, Thailand) with varied media height. Moreover, the wastewater preparation tank (2) was used to prepare the synthetic oily wastewater, consisting of plastic tank, pump and equalization tank (3).

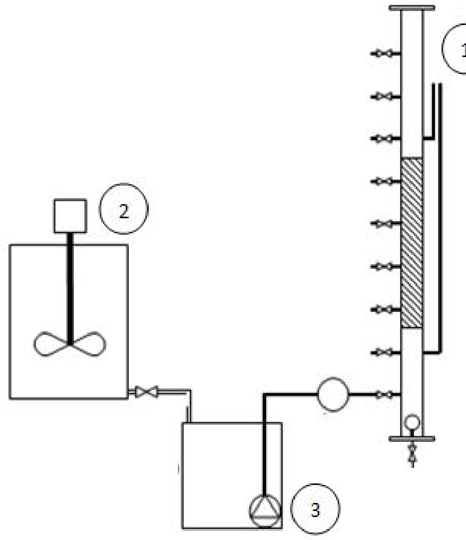
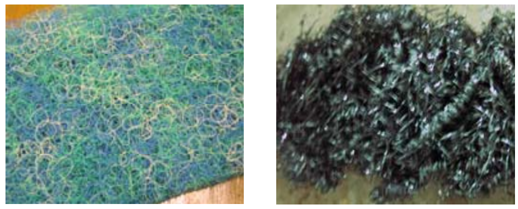


Fig. 1 Schematic diagram of coalescer apparatus in the experiment



(a) (b)

Fig. 2 Fibrous media used in this experiment (a) plastic fiber and (b) stainless fiber

B. Oily wastewater preparation

The synthetic oily-emulsion with surfactant used in this work was prepared from the mixture of tap water with 5,000 mg/L of palm oil (Morakot Public Company, Thailand) combined with anionic surfactant, SDS (Sodium Dodecyl Sulfate) at concentration 0.008 $mol{\cdot}l^{-1}$. Noted that this concentration correspond to the Critical Micelle Concentration (CMC) of this oily emulsion [14]. Then, the mixture was rapidly stirred at 300 rpm for 5 minutes [15] in order to obtain the stabilized oily emulsion with surfactant used in this experiment.

C. Analytical parameters

COD: this parameter was used to estimate the amount of oily wastewater. The COD level is analyzed by using close-flux method as described in Standard Methods (APHA-AWWA-WPCF, 1998) [16].

Oil droplet size distribution: the area under oil distribution curve was assumed to be related with oil quantity in the wastewater. Thus, the amount of removed oil can be calculated from the difference between the area under curve obtained with the influent and effluent. Note that the distribution curve was analyzed by applying microscope technique with scale and stage microscope apparatus [15].

Treatment Efficiency: the treatment efficiency was determined by the values of COD and area under curve. Moreover, the efficiencies from the experiment were compared with those from the predicting method based on the target collision efficiency equation [1]. Therefore, the treatment efficiency, in this work, can be calculated by equation (1).

$$\%Eff = \frac{COD_{in} - COD_{out}}{COD_{in}} \times 100 = \frac{Area_{in} - Area_{out}}{Area_{in}} \times 100 \quad (1)$$

D. Experimental operation process

In order to determine the associated parameters (fiber media properties, and suitable height of media bed), the batch process was chosen. Note that the experiments for analyzing the fiber properties were firstly applied for selecting the suitable coalescer media. The various parameters (contact angle between fiber surface and oil and also water droplets, critical surface tension, and density of the media) were analyzed. Moreover, the values of COD removal were applied as a parameter to indicate the treatment efficiencies for selecting of bed height to achieve the best result for wastewater treatment.

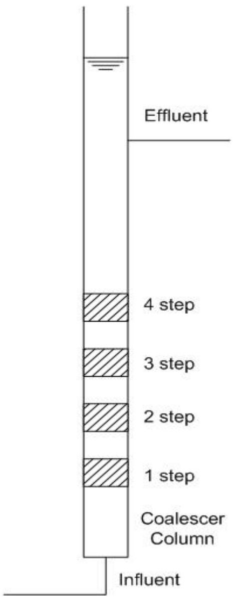


Fig. 3 Schematic illustration of coalescer column for step bed coalescer process

Influent flowrate of 5 l·hr^{-1} at liquid temperature of 303 K was used in the batch process both for the effect of media height and step bed coalescer process study: this flowrate correspond within the operating condition suggested for coalescer [4]. The applied media bed heights (3.5, 5, 7, 10, and 14 cm) were studied in order to obtain the suitable value for continuing the step-bed experiments for 1 to 4 step coalescers. Step bed media arrangement used in this study is demonstrated in Fig. 3 by using the bed height that produced the highest %Eff in the study of bed height effect with the interval equal to the applied bed height.

III. Results and Discussion

A. Coalescer media selection

In this part, the media properties were determined in term of the contact angle (θ_C), critical surface tension (γ_C), and fibrous porosity (ε). The media characteristics are shown in Table I.

TABLE I
Coalescer media characteristics

Type of media	Contact angle (θ)	Critical surface tension (γ_C)	Fibrous porosity (ε)
Stainless media	90.97°	33.36 mN·m^{-1}	0.91
Plastic media	87.89°	34.68 mN·m^{-1}	0.97

From the Table I, it can be noted that the values of θ_C and γ_C obtained with the plastic media were greater than those obtained with the stainless media: this can be implied that the plastic media is more hydrophobic than the stainless one. Therefore, the plastic media present the tendency for more oil particles attachment on media surface than the other one. The treatment efficiencies obtained with plastic media (44.4%) were greater than those obtained with stainless one (40.2%). Therefore, the plastic media will be applied, in this research, as a coalescer media bed in the next part.

B. Height of media coalescer

Fig. 4 presents the variation of the treatment efficiency (%Eff) with time for different coalescer bed heights and also compared with that obtained with the convention decantation process. Note that the values of %Eff presented in this study were calculated from the COD values as in (1). Moreover, batch process was applied with the liquid flow rate equal to 5 l·hr^{-1}.

As shown in Fig. 4, it can be firstly observed that the coalescer process can be applied in order to reduce COD values of stabilized oily emulsion with anionic surfactant (more rapid than the sedimentation process). Moreover, the different heights of coalescer media can affect the COD reduction rate and also the overall treatment efficiencies (%Eff): highest value was obtained with the shortest bed (3.5 cm). It can be stated that the oil droplets were attached in the early stage and then broken down due to the inertial force and pressure drop occurred in the later stage when the height of coalescer bed increases. The small oil particles will be thus generated and moved slowly to the surface based on the separating velocity from Stoke's law [2].

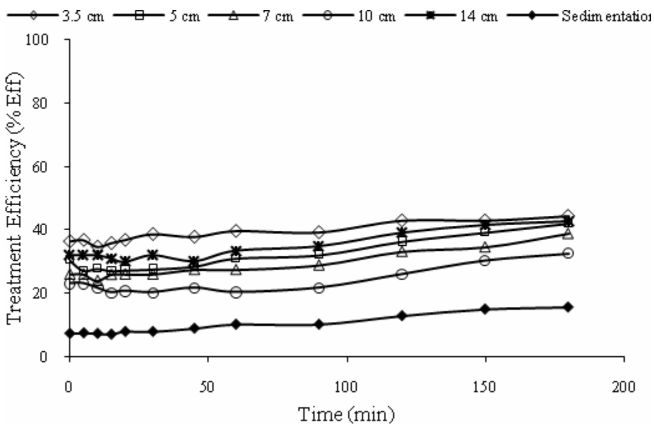


Fig. 4 Treatment efficiencies in function of time for different coalescer bed height

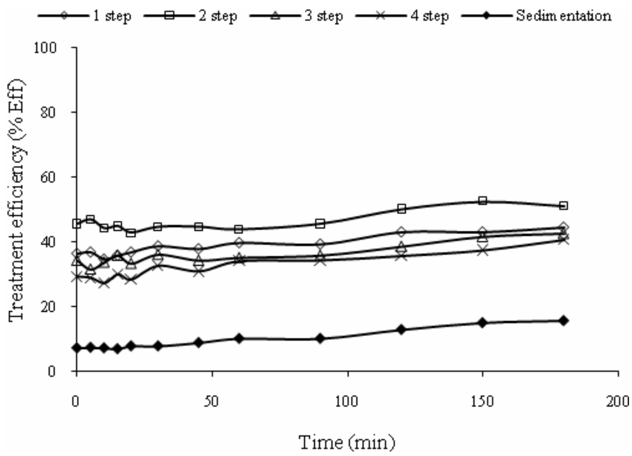


Fig. 5 Treatment efficiencies in function of time for different step bed coalescer

In this work, at coalescer height (3.5 cm), the treatment efficiency of 45% in COD values can be obtained within 180 minutes of operation times. Therefore, this height of coalescer bed will be then applied for the step-bed coalescer experiments, since high efficiency can be achieve with economize on the cost of coalescer media.

C. Effect of step bed coalescer

In the step bed coalescer experiments, the 3.5 cm media height was chosen for 1 to 4 steps. Fig. 5 presents the variation of the treatment efficiency (%Eff) with time for different number of step beds (N_{Bed}).

As shown in Fig. 5, the treatment efficiencies (%Eff) were influenced by different N_{Bed} values. The treatment efficiencies of 44, 51, 43, and 41 percent approximately of COD removed were acquired from 1 to 4 steps, respectively. It should be noted that the obtained %Eff from step-bed process were slightly higher than that of single bed with the same bed height, except for 14 cm media. The highest %Eff value was produced in the 2 step bed.

Hence, it can be concluded that the concept of step bed coalescer provided the higher coalescer performance for oily wastewater treatment compare to equal media bed height. The differences in term of collision and attachment mechanism between oil and media occurred were possibly the important factors and thus should be analyzed in order to well understand these phenomena.

D. Model of coalescer mechanism efficiencies

In this part, the model for predicting the treatment efficiencies obtained with coalescer process [1] will be proposed by applying Ergun's equations and the filtration efficiency in order to construct the oil droplet size distribution curve and also the associated area under curve after treating by coalescer process.

Firstly, the Ergun's equation (correlation of the friction factor in a spherical granular packed column as a function of Reynolds number) as in (2) will be used for determining the diameter of media related with the fiber coalescer media (D_P) used in this study [17].

$$\frac{\Delta p}{H} = \frac{150 V_0 \mu (1-\varepsilon)^2}{\psi^2 D_P^2 \varepsilon^3} + \frac{1.75 \rho V_0^2 (1-\varepsilon)}{\psi D_P \varepsilon^3} \quad (2)$$

The sphericity factor (ψ) of fiber media can be determined from the media bed height and diameter by using the specific interfacial area equation as in (3) [18].

$$\psi = \frac{A_{Sphere}}{A_{Particle}} = \frac{(36\pi V_{Particle}^2)^{\frac{1}{3}}}{A_{Particle}} \quad (3)$$

Note that the D_p value of 1.412 x 10^{-3} m can be determined from (2) by applying the ψ value (0.0161) and the measured values of media properties, including bed height (H) varied in this experiments, and the media porosity (ε) of 0.97. The operating conditions in terms of pressure loss (Δp) and liquid velocity were also considered. Then, the treatment efficiency of coalescer can be simply associated with the coalescence efficiency correlation as in (4) [1].

$$\ln\left(\frac{C}{C_0}\right) = -\frac{3}{2}(1-\varepsilon)\cdot\alpha\cdot\eta_T\cdot\frac{H}{D_P} \quad (4)$$

Based on the influent and effluent COD values, the values of $\alpha\cdot\eta_T$ can be calculated by applying (4) in this experiments and can be shown in Table II.

TABLE II
SINGLE COLLECTION (η_T) AND ATTACHMENT EFFICIENCY (α) AT DIFFERENT OPERATING CONDITIONS

Bed height (cm)	$\alpha\eta_T$
3.5	0.5695
5.0	0.3686
7.0	0.2390
10.0	0.1340
14.0	0.1346

No. of steps	$\alpha\eta_T$
1	0.5695
2	0.3471
3	0.1797
4	0.1270

However, by using the $\alpha\cdot\eta_T$ values in order to simulate the oil droplet size distribution curve and predict the overall treatment efficiencies, the predicted values tend to be lower than the experimental ones: the liquid phase characteristic (stabilized oily-emulsion) and the increase of bed height resulting to turbulent condition occurred were possibly responsible for these results. Therefore, the correction factor (β) was proposed in order to adjust the accuracy of the calculated efficiency. Note that this factor was combined with ratio of static surface tension (γ) and of bed height (λ). The γ value, defined as the surface tension ratio between dispersed and continuous phase will be applied in order to consider the effect of stabilized oil droplet on the media surface interaction and attachment. This can be determined from the surface tension of palm oil divided by one of aqueous solution with SDS at 303 K, which equal to 32.4 [19] and 41.0 mN·m^{-1}, respectively. Moreover, the effect of turbulence condition that probably plays a key role for longer bed height will be considered in term of media height proportion based on the optimal bed height ($H_{optimal}$) equal to 3.5 cm in this study. Therefore, the correction factor can be calculated from (5).

$$\beta = \gamma \cdot \lambda = \frac{H}{H_{Optimal}} \cdot \frac{\sigma_D}{\sigma_C} \qquad (5)$$

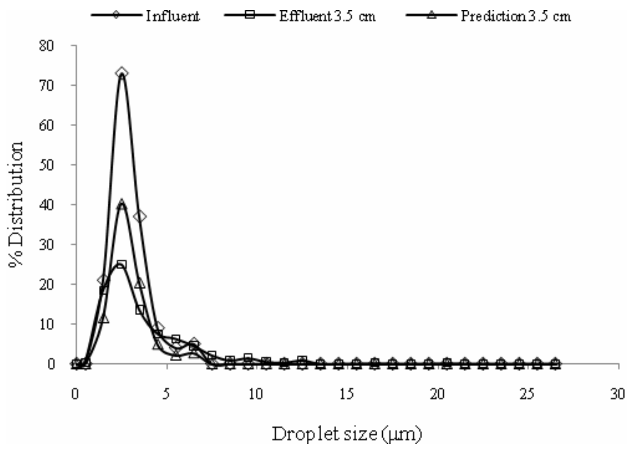
For stage coalescer, the turbulent effect was considered as the number of step bed as in (6).

$$\beta = N_{Bed} \cdot \gamma \qquad (6)$$

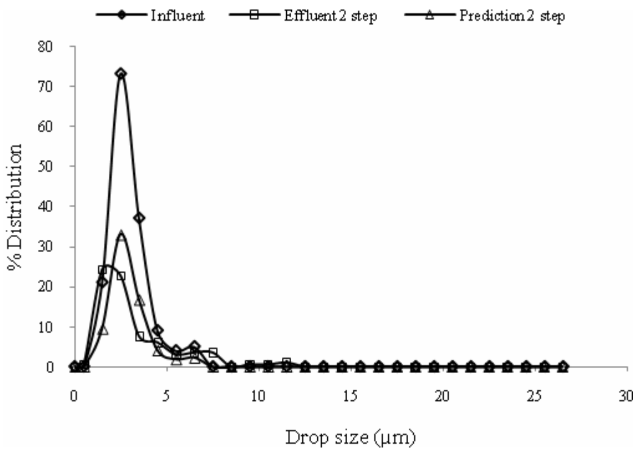
E. COD prediction model

In order to predict the size distribution curve and the area under curve after treating by coalescer process, the total efficiency of coalescer ($\beta\cdot\alpha\cdot\eta_T$) related with different oil droplet size will be thus applied.

As shown in Fig. 6, the size distribution of oil droplets in the influent wastewater indicated that the varied sizes of oil droplet were contained in water, especially the small droplet (D_E < 10 μm). By applying the calculated total efficiency, the size distribution of oil in water after treating for every study condition can be determined. Moreover, the related area under curve can be thus calculated by the numerical integration method: these decreasing in area under curve correspond with the COD removal by coalescer process. In this work, smallest area (67.28) were obtained in the case of 2 step-bed coalescer: this conforms with the related effluent COD values and also treatment efficiency as previously described.



(a)



(b)

Fig. 6 Size distribution of oil-in-water dispersion of influent and the graph area reduction by model for (a) 3.5 cm bed height and (b) 2 step bed coalescer

Regarding to the variation of calculated area under curve, the simple model for predicting the effluent COD values can be proposed as in (7). Therefore, the relation between remaining area under curve and effluent COD values from coalescer can be obtained. The outcome of this prediction model can be presented as in Fig. 9.

$$COD_{out} = Area_{out} \times \frac{COD_{in}}{Area_{in}} \qquad (7)$$

As presented in Fig. 7, the COD remaining calculated from the prediction model tend to have the close value compared to those obtained from the experiment results with the difference of 20% approximately, since the model used in this study included only coalescence mechanisms. Therefore, it can be concluded that the COD prediction from area under size distribution curve by applying the model proposed from efficiency model equation produced an acceptable accuracy.

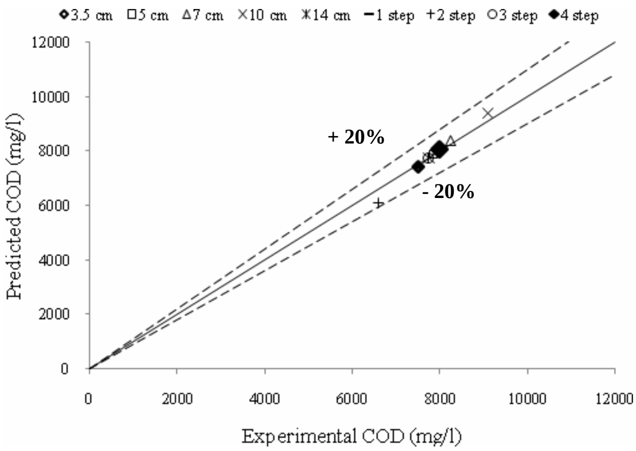


Fig. 7 Comparison of experimental and model-predicted COD

However, in the future, more experimental data are necessary and other mechanisms between oil droplets and media (i.e. surface sorption) should be further investigated and included in the proposed model in order to achieve more accuracy prediction and also for validation the proposed model.

IV. Conclusion

The objective of this research is to study the effect of different operating parameters (media types and bed height) and also step-bed coalescer concept on the treatment of oily emulsion with anionic surfactant by coalescer. In this study, the following results have been obtained:

- The plastic fiber media was more suitable to be used as coalescer media due to its hydrophobic property which is probably well attached with oil particles;
- The different heights of coalescer media can affect the overall treatment efficiencies: the largest values of %Eff were obtained with the shortest media height;
- The treatment efficiencies obtained with step-bed coalescer were higher than those obtained with the conventional coalescer process with the same bed height.
- The predicting model proposed can provide relatively a good coincidence between the experimental and predicted values of treatment efficiencies in this study.

In the future, more experimental data are necessary to accurately propose and also validate these correlations. Moreover, other oily emulsions with different types of surfactants (cationic and non-ionic), different coalescer media and operation processes should be tested to extend the operating condition ranges.

Acknowledgment

This work has been carried out within the financial support of the Thailand Research Fund (TRF), and the Silver Jubilee Fund, Chulalongkorn University.

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