

Study Towards Cleaner Production by Palm Oil Mills: Modelling of Oil Separation for Horizontal Settling Tank

J. Chungsiriporn^a, S. Prasertsan^b and C. Bunyakan^c

^a The Joint Graduate School of Energy and Environment (JGSEE)
King Mongkut's University of Technology Thonburi,
Bangkok, 10140, Thailand

^b Department of Mechanical Engineering, Faculty of Engineering,

^c Department of Chemical Engineering, Faculty of Engineering,
Prince of Songkla University, Hat Yai, Songkhla, 90112, Thailand
Tel: 66-7421-2896, Fax: 66-7421-2896

E-mail: cluntima@ratree.psu.ac.th

(Received : 15 January 2005 – Accepted : 30 March 2005)

Abstract: The horizontal settling tank is common equipment for oil separation in the wet milling process of crude palm oil mills. It was found that 7-10% of palm oil is present in the discharging sludge. To improve the settling efficiency, the influence of settling variables was studied to form a mathematical model of the horizontal settling process. Settling behavior of the oil-sludge mixture was studied in a laboratory and the results were applied to a horizontal continuous flow settling tank in a factory. The regression models were validated statistically by the analysis of variance (ANOVA), coefficient of multiple

determination R^2 and P-value approaches. The settling model reveals that the increase of temperature, palm oil ratio in feed and settling tank volume, together with the decrease of feed flow rate and water ratio in the sludge phase can reduce the palm oil residue in the discharging sludge. The model satisfactorily agrees with the modified Stokes' law. The settling model is used to predict the settling tank provides options and suggest for cleaner production by minimizing water consumption.

Keywords: Settling tank, settling time, regression model, palm oil mill.

Introduction

Oil palm is an important economic crop in South East Asia. Production of palm oil a serious contributor to pollution because of the heavy organic load in wastewater discharge. The milling by wet process accounts for 75-80% of palm oil extracting capacity in Thailand (H - Kittikun et al. 2000). The wet process consumes a large amount of process water and, subsequently, generates an even larger amount of palm oil mill effluent (POME) with substantially high pollution load. Approximately, 0.87 tonnes of POME is generated for each ton of fresh fruit bunch (FFB) processed (Prasertsan and Prasertsan 1996). The water is utilized to enhance the ability of extraction, separation, and fluidity (flow ability) of extracted liquid, which is a three-phase mixture of oil, water and solids. An attempt to introduce cleaner production concepts has surfaced recently and

the palm oil mills are potential candidates. There is a need for process water management to reduce water consumption, wastewater generation and oil loss in the milling process. However, this could be achieved only if the operating characteristics of water-consuming operation units are well understood. This paper presents the first part of a study aiming to minimize water consumption in the milling process. It reports a study to determine the formulation of settling models of oil in the settling tanks, which is essential for further study of potential improvements.

Palm oil milling process

The palm oil milling process consists of sterilization, fruit stripping, digestion, extraction, oil separation, and oil recovery. The schematic diagram of the process is shown in Fig 1. The fresh fruit bunch (FFB) is sterilized by steam at 2-3 bar (120-130°C) for 50-60 minutes to terminate enzyme activity, otherwise free fatty acids could develop and degrade the oil quality. The steam loosens the fruit which are subsequently stripped by a rotary thresher. The fruit is digested in the digester with the aid of hot water (80°C). The screw press extracts a mixture of oil, water and suspended solids from the fruit fiber and nuts. A vibrating screen removes large particles in the extracted mixture. This process requires the addition of water to improve screening effectiveness. Following this the mixture is transferred to the settling tanks where oil is separated from sludge by gravity.

The light (mostly oil) phase overflows through conical receivers and then through a purifier to remove moisture. The sludge leaves as bottom product. It contains fraction of palm oil, which is recovered by a train of a decanter and a centrifuge separator. The quantity of freshwater used to balance the phases in these oil recovering units depends on the oil and solid content of the sludge. Outlet wastewater from the separator generally contains 0.7-1.0% oil.

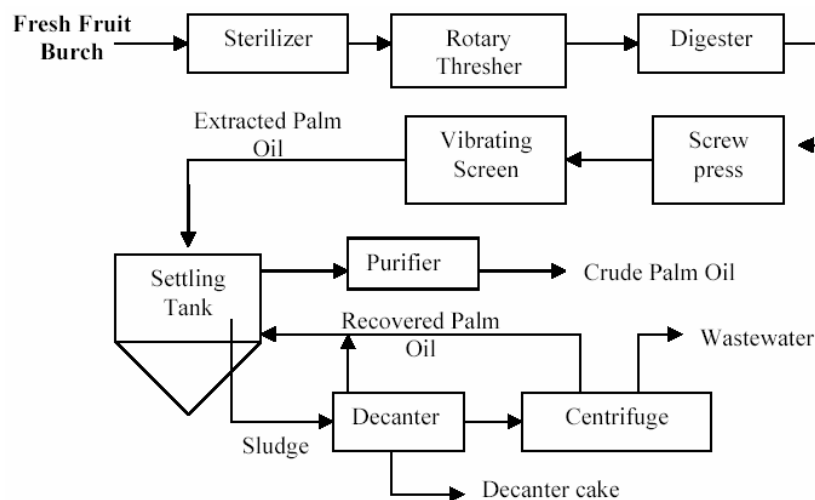


Figure 1. Schematic diagram of palm oil milling process.

Modelling of the settling tanks and statistical validation

Settling is a physical separation process of different phases in mixture. The force of gravity leading to the formation of distinct light oil and sludge interface impels the settling

material. Particles heavier than the suspending fluid can be removed in the settling tank, in which the fluid velocity is low and the particles have ample time to settle down. Incomplete separation during the settling process leads to the presence of palm oil in the sludge. The amount of the residual oil reflects the efficiency of the settling tank, which affects the subsequent oil recovery process.

Two types of settling tanks namely, vertical and horizontal, settling tanks are widely used in palm oil mills. The vertical settling tank is a conical bottom vessel in which the mixture is gently stirred for uniform heat and mass transfer. The light phase of palm oil slowly flows upward while the heavy sludge flows downward. The horizontal settling tank is a series of rectangular tanks through which the process stream flows in a horizontal direction and the settling occurs during the course of flow.

A regression model is used to represent the results of experiments. Typical quadratic model (Eq.1) is employed to express the relationship between dependent and independent variables. Selection of significant variables for inclusion in this empirical model is carried out by Microsoft Excel statistical package. The multiple regression is determined and the elimination of non-significant terms is performed having the level of significance ($P\text{-value} < 0.05$) as criteria. A low P value of a particular independent variable indicates its significant role in improving the curve fitting of the model.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \left(\sum_{i=1}^{k-1} \sum_{j=i+1}^i \beta_{ij} x_i x_j \right)_{i < j} \quad (1)$$

The validity of the model is tested by the following hypotheses.

$$H_0 : \beta_1 = \beta_2 = \dots = \beta_k = 0$$

$$H_1 : \beta_j \neq 0 \text{ for at least one } j$$

If at least one β_j is not equal to zero, the model is considered valid. H_0 is the null hypothesis used for verification of the regression model. Rejection of H_0 is essential as an indicator of the presence of significant terms in the model. The hypothesis is checked by comparing the calculated F with the critical value (i.e., using F statistics). The sources of variability are identified by analysis of variance (ANOVA) approach. The ANOVA test procedure involves the term "sums of squares" which measure the variability due to the levels of significance and due to the errors. The general form is,

$$SS_T = SS_R + SS_E$$

where, SS_T is the total sum of squares, SS_R is the sum of squares due to regression, and SS_E is the sum of squares due to errors.

The hypothesis test procedure for null hypothesis $H_0 : \beta_1 = \beta_2 = \dots = \beta_k = 0$ is determined by,

$$F_0 = \frac{SS_R / k}{SS_E / (n - k - 1)}$$

With a level of significance of α , the null hypothesis is rejected if,

$$F_0 > F_{crit} = F_{\alpha, k, n-k-1}$$

Level of significance of each factor is set by the P-value of less than 0.05. The regression output also reports the coefficient of determination or R^2 . It is the proportion of variability accounted for the regression written as,

$$R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T}$$

R^2 measures of the amount of reduction in the variability of y . However, a large value of R^2 does not necessarily imply a good regression model, because R^2 always increases as more terms are added to the model. In this respect, it is preferable to use adjusted R^2 statistics; the term which does not always increase with the adding of variables to the model. R_{adj}^2 is defined as,

$$R_{adj}^2 = 1 - \frac{SS_E / (n - p)}{SS_T / (n - 1)} = 1 - \left(\frac{n - 1}{n - p} \right) (1 - R^2)$$

If R_{adj}^2 is not significantly different from R^2 , non-significant terms have not been included in the model.

Experimentation

The palm oil separation experiments were conducted in both vertical and horizontal settling tank systems. The vertical settling experiment gives the effect of gravity on the settling characteristics with respect to independent variables. It was carried out on a laboratory scale container. The horizontal

settling experiment was performed with a settling tank at the mill.

1. Batch vertical settling experiment

The batch vertical settling experiment was carried out in a 2-litre laboratory glass container equipped with a stirrer and a heater. The feed of palm oil mixture was obtained from Taksin Palm Oil Mill in the south of Thailand. The samples were collected from the entry point of the settling tank. The mixture is considered as having 2 phases, which are sludge (the mixture of solids and water) and palm oil. The feed composition, in terms of water, solid and oil content, was determined by the centrifugal method. The compositions were in the range of 0.50-0.65 kg of water, 0.30-0.40 kg of palm oil and 0.05-0.15 kg of solids per kilogram of feed mixture. Initially, 1.8 litres of the sample were agitated and heated to the predetermined settling temperature (independent variable). When reaching the required temperature, the stirrer and the heater were removed. Distinct interface of sludge sediment and the supernatant liquid palm oil appeared as the settling process progressed. The interface slowly proceeded downward. The height of the interface and the corresponding settling time were recorded for every 50 ml change of the interface. The tests ended when the interface height was equivalent to 1.3 litre. Thirty five experiments were carried out to cover the experimental range of independent variables. The settling times at interfacial heights equivalent to 1.65 litres were used to form the settling time model.

2. Continuous settling experiment

The continuous horizontal settling experiment was performed with the existing horizontal setting tank at the mill. The settling unit consists of two rectangular tanks, interconnected by a weir. The diagram of the continuous horizontal settling tank settling is shown in Fig.2.

The feed is continuously pumped to the receiving tank before flowing horizontally through the settling tanks. Steam coils are used to control settling temperature at 90-97°C. Vertically-adjustable conical receivers remove the palm oil (the upper phase), which is sent to the purifying unit to produce crude palm oil as the final product. Sludge is drawn from the bottom of the tank. The oil residue in the sludge is recovered by a decanter and centrifugal separator. The recovered oil is then sent back to the settling tank.

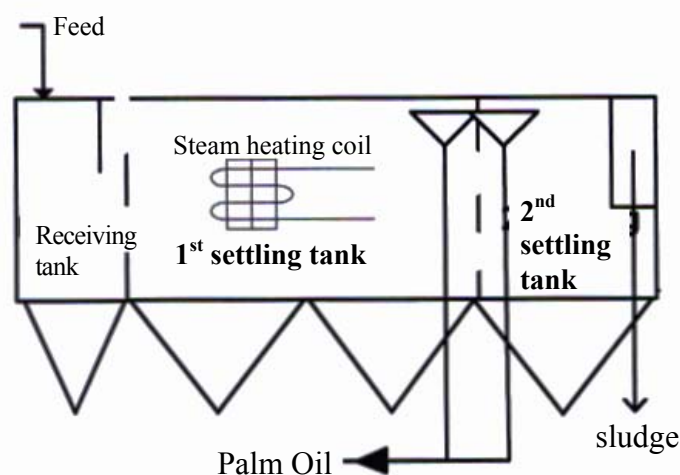


Figure 2. Field horizontal settling tank experiment.

Settling independent variables are temperature, settling volume, feed composition and feed flow rate. The independent variables were continuously monitored and recorded. The feed and the sludge were sampled for every 30 minutes and analyzed for their composition. The volumetric composition of the feed was determined by tube centrifuge and subsequently calculated by weight composition. The percentage of oil content in the sludge was determined by Partition-Gravimetric method.

A mathematical model of the settling process was formed by fitting the experimental data with a full quadratic equation processed by Microsoft Excel statistical package. Backward elimination and ANOVA were carried out to determine the significant terms with P value of less than 0.05.

Results and Discussion

1. Settling time model of batch settling

The settling time model was constructed from experimental data of the batch settling experiment. The settling time determines how easily palm oil is separated by the gravitational settling process. Any decrease of settling time enhances the settling efficiency. The settling time in this study is specified by the time required for the light phase to separate by 0.15 litres (from the mixture of 1.8 litres).

The settling parameters influencing the settling time are temperature, water content in sludge phase and palm oil

content in the feed stock. The experimental results revealed that the sample had a very low separation rate at settling temperature of less than 90°C. A settling time model describing the influence of the settling parameters was obtained by data fitting and is given in Eq.2, where all insignificant terms were eliminated. The output of statistical analysis is given in Table 1. The most significant term of the regression model is x_T ($P = 6.871e-05$).

$$S_t = 91.28 - 1.486x_T + 2.851x_Tx_o - 367.43x_o x_w + 95.98x_w^2 \quad (2)$$

where S_t is settling time (min), x_o is oil content in feed, x_w is water content in sludge phase and x_T is settling temperature (°C).

The regression sum of squares for settling time model with 4 degrees of freedom is 155.75. From the test statistics, $F_o = 63.49$ and the critical value $F_{0.05,4,34} = 2.65$. Since $F_o > F_{0.05,4,34}$, the null hypothesis is rejected and we can conclude that at least one independent variable contributes significantly to the regression model. This implies that there is a statistically significant dependency of the settling time on the independent variables. The figure of R^2 is 0.894. In other words, 89.4% of the variance in S_t is accounted for by the model. Since the adjusted R^2 (0.880) is very close to R^2 , all terms in Eq.2 are significant.

The model is a function of linear, square and 2 interaction terms of 3 parameters. The analysis of variance indicates that the oil ratio in feed (x_o) water ratio in sludge phase (x_w) and settling temperature (x_T) significantly influence the settling time.

Settling temperature, with the lowest P-value, is the most significant parameter in prediction of the settling time.

Table 1. ANOVA of vertical settling experiment.

<i>ANOVA</i>					
Source	Sum of Squares (SS)	SS%	MS	F	df
Regression	155.75	89	38.94	63.49	4
Residual	18.40	11	0.613		30
Total	174.15	100			34
R^2	= 0.894				
R^2 adjusted	= 0.880				
Std. error	= 0.783				
Independent variable	Coefficient	P value	Std. error	t Stat	
Constant	91.28	1.863e-06	15.48	5.896	
x_T	-1.486	6.871e-05	0.322	-4.616	
$x_o x_T$	2.851	0.00495	0.940	3.034	
$x_o x_w$	-367.43	0.00173	106.77	-3.441	
x_w^2	95.98	0.000255	23.15	4.146	

The role of each parameter is explained by 3-D response surface plots as shown in Fig.3. It shows that the increase of oil content and settling temperature and the decrease of water content in the sludge phase shorten the settling time. This tendency agrees with the previous study by Hulston et al. (2003). However, it was apparent that the settling temperature has a limit of not higher than 97°C, otherwise the process is

disturbed by turbulence resulting from the formation of gas bubbles in the mixture. To enhance the settling process, addition of water to the upstream processes (the digester, screw press and the vibrating screen) should be reduced. However, there is a minimum requirement of additional freshwater in order to help the equipment work effectively. The minimization of water added to the upstream processes could eventually increase the oil ratio in the mixture, which results in better settling ability. This, fortunately, is the practice of cleaner production by the concept of source (of waste) reduction which is the aim of this work (to be reported a later paper).

In general, the settling time is shortened if the settling material has high terminal velocity. The settling terminal velocity of the modified Stokes equation (Christi 1995) is shown in Eq.3. The equation shows that the increase of density difference between sludge and palm oil, the increase of volume fraction of palm oil in the mixture, and the decrease of palm oil viscosity, contribute to the increase of the terminal velocity.

$$v_t = \frac{gD^2(\rho_p - \rho)}{18\mu}(\varepsilon^2\psi_p) \quad (3)$$

where V_t is terminal velocity (mls), D is droplet diameter (m), g is acceleration due to gravity (9.81 mls^2), ρ_p is sludge density (kg/m^3), ρ is oil density (kg/m^3), μ is viscosity of continuous phase (pa.s), ε is the volume fraction oil in mixture and ψ_p is empirical correction factor.

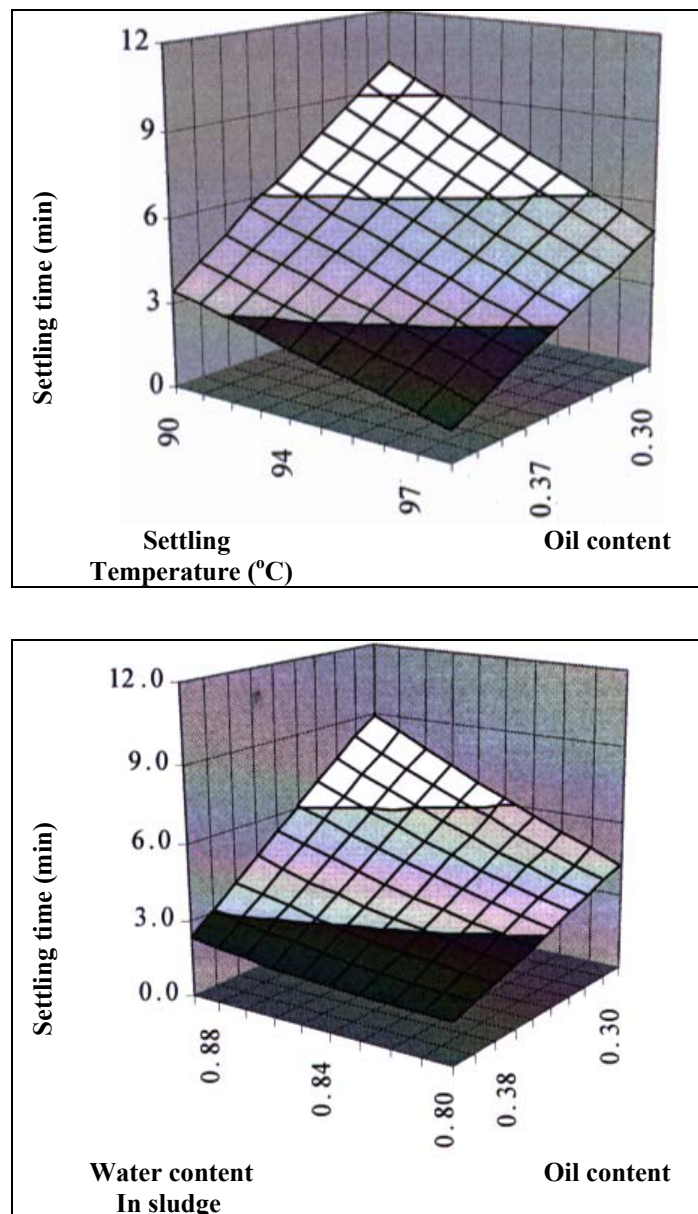


Figure 3. Response surface plots for batch settling tests.

The dependency of the settling time on the experimental variables agrees well with the modified Stokes equation. The less water added to the upstream process actually increases the sludge density and, hence, increases the density difference of the palm oil and sludge. It also increases the palm oil volume fraction in the mixture. Higher settling temperature reduces the palm oil viscosity. Such changes lead to a decrease of the settling time as observed in Fig.3.

2. Settling model of continuous horizontal settling tank.

The continuous horizontal settling tank is different from batch settling in the way that it is fed continuously and the sludge-oil interface appears as, more or less, a constant line. Apart from applying the vertical batch settling results, the continuous-feed horizontal settling model includes two more parameters namely; feed flow rate and settling volume (Johnston and Simic 1991). As a result, settling parameters are classified into two groups; the settling terms and the dynamic terms. The settling terms consist of settling temperature and feed composition. The dynamic terms are the feed flow rate and settling volume, which are combined to form a new term called “retention time” (Larock et al.1983). The retention time is the time that the settling material is present in the settling tank (Eq. 4).

$$Rt = \frac{V}{Q} \quad (4)$$

where Rt is retention time (hrs.), V is settling volume (m^3) and Q is feed flow rate (m^3/h).

Both (batch) settling time and retention time play an important role in settling efficiency, which is reflected by the quantity of palm oil residue in the sludge. The retention time, the settling time and the percentage of palm oil residue in the sludge then form a mathematical model for the horizontal settling process. The result is expressed as Eq.5 and statistical analysis is presented in Table 2.

$$S_e = (0.00407 + 0.0495R_t - 0.000165S_t^2)^{-1} \quad (5)$$

where S_e is percentage of palm oil in sludge, R_t is retention time (hrs.) and S_t is settling time (min).

Table 2. ANOVA for horizontal continuous flow settling efficiency model.

<i>ANOVA</i>					
Source	Sum of Squares (SS)	SS%	MS	F	df
Regression	0.02107	83	0.01054	58.49	2
Residual	0.00432	17	0.000180		24
Total	0.02539	100			26
$R^2 = 0.830$					
R^2 adjusted = 0.816					
Std. error = 0.0134					
Independent variable	Coefficient	P value	Std. error	t Stat	
Constant	0.00407	0.688	0.01000	0.407	
R_t	0.04949	1.227e-10	0.00461	10.73	
S_t^2	-0.000165	0.000132	3.626e-05	-4.544	

It is apparent that the retention time, R_t (P-value = 1.001e-10) and the squares of settling time, S_t^2 (P-value = 9.915e-5) are very significant for the determination of oil

residue in the sludge (S_e), which represents the efficiency of the settling process. The data fitting has R^2 and R^2_{adj} of 0.830 and 0.816, respectively. The regression sum of squares for settling efficiency with 2 degrees of freedom is 0.02107 and $F_o > F_{o,05,2,26}$. This implies that the model is statistically valid.

The 3-D response surface of the oil residue has been plotted (Fig.4). The decrease in settling time and the increase in retention time enhance the separation efficiency, as apparent by the low percentage of oil residue in the sludge.

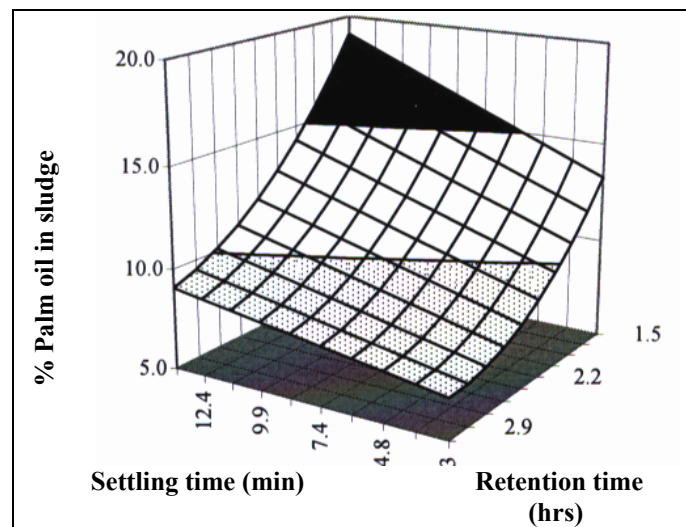


Figure 4. Response surface plot for horizontal continuous settling process.

By substituting Eqs.2 and 4 in Eq.5, the relationship of all process variables in the settling efficiency of the horizontal settling tank is obtained (Eq.6).

$$S_e = \left(\frac{0.00407 + 0.0495V/Q - 0.000165(91.28 - 1.486x_T)^{-1}}{+ 2.851x_Tx_o - 367.43x_o x_w + 95.98x_w^2} \right)^{-1} \quad (6)$$

The model can be used to predict the settling efficiency and suggest improvements to the settling process (to achieve low oil residue in the sludge). In conclusion, the increase of settling volume, palm oil content (in the palm oil mixture) and settling temperature, along with the decrease of feed flow rate and water content (in sludge) will give higher settling efficiency.

As the settling volume is generally fixed in the palm oil mills, the retention time thus depends on the feed flow rate. Since the feed flow rate depends on the mill's production capacity, it is inevitable that the maximum settling efficiency is achievable at the expense of productivity limitation. The productivity and efficiency are both cost factors for the mills, which need careful attention in production management. It is suggested that the oil settling system should be a set of tanks installed in parallel trains to cope with the seasonal variation of the productivity (or milling capacity).

The minimization of water added to the process could both decrease water content in the sludge phase (x_w) and increase palm oil content in the feed (x_o), which consequently increases the process settling efficiency. The data collected from the mill shows that the minimum figure of water content in the sludge phase is 0.30. It therefore preliminarily suggests that the mill that is operating with x_w greater than 0.30 is wastefully using the process water and unnecessarily paying a higher wastewater treatment cost.

The high efficiency of the settling process also results in less water used in the downstream oil recovering units. The palm oil remaining in the sludge is recovered by a decanter and a centrifuge separator. These units require the addition of water, otherwise the oil recovery is inefficient. Less oil in the sludge requires less additional water in the decanter unit. Minimization of the water demand and optimization of the milling process to reduce both processing and environmental costs is presented in the second part of this study.

Conclusions

This study aimed to obtain a mathematical model that explains the settling behavior in a horizontal continuous settling tank. The model was derived from data of the batch vertical settling experiment, settling tank capacity and feed flow rate. The model, by using the multiple regression method, expresses the effect of the settling factors in quadratic form. Settling volume, temperature, feed flow rate and feed composition are settling factors of interest. Analysis of the settling tank process factors help our understanding of oil separation in this unit. The model is then used to suggest improved operation of the milling process for cleaner technology and less production cost. In conclusion, it was found that,

1. Having high settling temperature, settling volume and palm oil content and low water content and feed flow rate can improve the settling efficiency.

2. To get high settling efficiency and avoid turbulent flow of the feed due to gas bubble formation, the settling temperature should be in the range of 90-97°C.
3. The addition of water in the upstream processes should be minimized so that the water ratio in the sludge phase is not unnecessarily high and high settling efficiency can be achieved.
4. The high separation efficiency at the settling tank is the starting point for CT as, consequently, less water is needed in the downstream process.

Acknowledgement

The authors greatly appreciate the financial support of the Graduate School of Energy and Environment. We would also like to thank Taksin Palm Oil Company Ltd. for their support and use of the laboratory set up in their plant.

References

- [1] Christi, J. G. (1995) Transport Processes and Unit Operations, 3rd Prentice-Hall International, Inc.
- [2] Hulston, J., de Kretser, R.G. and Scales, P. J. (2003) Effect of temperature on the dewaterability of hematite suspensions, *Int. J. Miner. Process.*
- [3] Johnston, R. R. M. and Simic, K. (1991) Improving thickener operation and control by means of a validated model, *Minerals Engineering*, **4**, pp. 695-705.

- [4] Kittikun, A. H., Prasertsan, P., Srisuwan, G. and Krause, A. (2000) Environmental Management for Palm Oil Mill, *Internet conference on material flow analysis of Integrated Bio-Systems*.
- [5] Larock, B. E., Chun, W. K. C. and Schamber, D. R. (1983) Computation of sedimentation basin behavior, *Water Res.* **17**, pp. 862-867.
- [6] Prasertsarn, S. and Prasertsarn, P. (1996) Biomass residues from palm oil mills in Thailand: an overview on quantity and potential usage, *Biomass and Bioenergy*, **11**(5), pp. 387-395.