Heavy Fraction Separation From Used Lube Oil Using Thin Film Evaporator

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Abstract. Used lube oil is a dangerous waste that must be treated before disposed on the environment. Used lube oil treatment process consists of several stages, one of them is the separation of heavy fraction. Some equipment system can be used to complete this process, and thin film evaporator (TFE) is chosen for this research. The goal of this research is to understand the effect of temperature and rotor rotation on the heat transfer that happens in the distillation process using thin film evaporator. Simulation using Aspen Plus is used and is validated by manual calculation using Matlab. Temperature is varied between 250 – 330 °C and rotor rotation are varied between 0 – 60 rotations per minute (RPM) in a vacuum pressure of 2.53 kPa. From this research, the relation between operating temperature and rotor rotation in thin film evaporator to the vapor fraction produced is directly proportional. The optimum operating condition in this research was found at a temperature of 310 °C with the agitator rotational speed of 30 RPM.

1. Introduction
Used lube oil is a valuable resource. However, in its use, used lube oil is contaminated with various components of impurities. In addition, the organic constituents in lube oils also undergo changes during its use and produce contaminants. Thus, the used lube oil can no longer be used for several reasons. Because of the basic characteristics of used lube oil and these contaminants, the used lube oil cannot be discharged directly into the environment. Therefore, it needs further treatment for this used lube oil. There are several solutions to deal with used lube oil. The first way is to use used lube oil as a fuel. For more economically and environmentally feasible to handle the used lube oil, reprocess the used oil back into the fresh lube oil which can be used for the original requirement. There are several methods for treating used lube oil, one of them is intended to separate the heavy fraction of lube oils free of the residue using Falling Film Distillation Column [1]. The second method is using agitated thin film evaporator as the processing equipment [2]. In this separation process, the thin film evaporator as one normally will distribute the feed distilled at the wall of the evaporator. The thin layer thus formed and be separated, light fraction will go to the distillate, while the heavy fraction will be heading to the residue. The heating can be done in two ways, namely by using a heating coil in the evaporator or by using heat in the beginning before it goes into the evaporator. Thin film evaporator offers the dual advantage of short residence time and the formation of a thin film which optimizes the separation process. Therefore, it is necessary to design the thin film evaporator using simulation software Aspen Plus. The goal to determine the effect of operating temperature and rotor rotation thin film evaporator. After that, simulation results are validated using MATLAB and the optimum operating conditions are determined for this separation process according to specifications feed used in this study.
2. Theory

2.1. Used Lube Oil

Used lube oil is usually composed of a mixture of various lubricating oils that have been used in motor vehicles and industry. [3]. Lubricating oils lose their effectiveness because of specific types of contaminants. These contaminants are divided into two categories, the first is a foreign contaminant and the second is the product of damaged lube oil. Foreign contaminants come from the air and metal particles from the engine. Contaminants which come from the air are sand, dirt, and humidity. The air itself can be considered as a contaminant because it may cause oil or lube oil becomes frothy. Contaminants coming from the engine are metal particles due to the use of machines, carbon particles originating from incomplete combustion, metal oxides originating from corrosion on metal, water from leaking cooling system, the water of the products of combustion, fuels or additives or by-products which may enter the engine crankcase. [3]. Used lube oil has a chemical formula of carbon chain between C21-C40. Volatile gases contained in the used lube oil are H2, CO, and CO2. The composition of the used lube oil used in this study is described in Table 1 below:

| Component   | Mass Flowrate (kg/h) | Mass Percentage (%) |
|-------------|----------------------|---------------------|
| Light End   | 0.0001               | 0.00                |
| Gas Oil     | 0.6758               | 7.30                |
| Lube Oil    | 5.7667               | 78.37               |
| Residue     | 1.3273               | 14.33               |
| **Total**   | **9.2623**           | **100.00**          |

2.2. Thin Film Evaporator

Thin film evaporator is one type of evaporator that applies a formation of the thin layer in the heat exchange process. Despite this consideration, thin film evaporator is also considered as mass transport equipment because the molecules of the liquid phase may be transferred to the gas phase during the evaporation and vice versa. Stripping is done by the upward gases and absorption is done by the downward liquid. This equipment has been applied in the production of chemicals, pharmaceuticals, and food since 1950. Illustration of vertical thin-film evaporator is given in Figure 1:

![Figure 1: Vertical Thin-Film Evaporator](image-url)
3. Methods

Thin film evaporators are modeled on Aspen Plus using a combination of horizontal heat exchangers and vertical flash drum [6] according to Figure 2. This model is an approximation since there is no thin film evaporator as a single unit in Aspen Plus. Therefore, it needs validation using manual calculation. In this process, feed enters into the heat exchanger with temperatures of 200 °C and will be heated to 250-330 °C with increments of 20 °C. Then the value of the heat coefficient is entered which corresponds to variable rotor rotation 6-60 RPM at an operating pressure of 2.53 kPa. The liquid phase and vapor phase are then separated using a flash separator to obtain a top product and bottom product from the thin film evaporator. The value of the heat transfer coefficient (hsc) will change as the value of rotation of the rotor on the thin film evaporator changes. To get the hsc value, calculations are necessary and involve a wide range of variables with the following equation:

Figure 2: Thin-Film Evaporator Model

\[
\%L_v = \frac{\sum_{i=1}^{k} m_{vk}}{m_z} \times 100 \quad (1)
\]

\[
m_{vk} = \frac{Q_k}{\lambda_s} \quad (2)
\]

\[
Q_k = h_{sc,k} A_k (T_w - T_s) \quad (3)
\]

\[
h_{sc,k} = 2 \frac{k_s \rho_k C_p_k}{\pi t_e} \quad (4)
\]

\[
k_k = X_{L,k-1} k_L + (1 - X_{L,k-1}) k_h \quad (5)
\]

\[
\rho_k = X_{L,k-1} \rho_L + (1 - X_{L,k-1}) \rho_h \quad (6)
\]

\[
C_p_k = X_{L,k-1} C_p_L + (1 - X_{L,k-1}) C_p_h \quad (7)
\]

\[
t_e = \frac{1}{nB} \quad (8)
\]
\[ A_k = H_i \pi D_s \]  \hfill (9)

\[ H_i = \pi \cdot D_s \cdot \sin \phi \]  \hfill (10)

\[ \phi = \tan^{-1} \frac{V_z}{V_t} \]  \hfill (11)

\[ V_z = \frac{m_z}{A_i \rho_a} \]  \hfill (12)

\[ V_t = \pi D_t \cdot n \]  \hfill (13)

\[ A_i = \left( \frac{\pi}{4} \right) (D_s^2 - D_t^2) \]  \hfill (14)

\[ T_w = T_h - \frac{Q}{H_h A_h} \]  \hfill (15)

\[ T_h = \frac{T_{hi} - T_{ho}}{2} \]  \hfill (16)

\[ Q = m_z C p_h (T_{ho} - T_{hi}) \]  \hfill (17)

\[ h_h = \frac{N_u \cdot k_h}{D_e} \]  \hfill (18)

\[ D_e = D_{oj} - D_{ij} \]  \hfill (19)

\[ Nu = 0.023 \Re^{0.8} \Pr^{0.4} \]  \hfill (20)

\[ \Re = \frac{D_e V_h \rho_h}{\mu_h} \]  \hfill (21)

\[ V_h = \frac{m_h}{A_h \rho_h} \]  \hfill (22)

\[ A_h = \frac{\pi}{4} \left( D_{oj}^2 - D_{ij}^2 \right) \]  \hfill (23)

\[ Pr = \frac{C p_h \mu_h}{k_h} \]  \hfill (24)

\[ A_h = \frac{\pi}{4} \left( D_{oj}^2 - D_{ij}^2 \right) \]  \hfill (25)
With all of the equations above, the overall heat transfer coefficient can be obtained with varying the rotation of the rotor thin film evaporator (N). Heat transfer coefficient values obtained from manual calculations will be used into the simulation Aspen Plus. This overall heat transfer is also used to calculate how much product is separated using thermodynamic relation to validate the simulation results so that the error can be known. In this case the required data according to Tables 2 and 3.

**Table 2: Thin Film Evaporators Specification**

| Specification          | Symbol | Unit | Value |
|------------------------|--------|------|-------|
| Blade Diameter         | Dₐ     | m    | 0.0446|
| Outer diameter of the  | D₆     | m    | 0.0720|
| annulus                |        |      |       |
| Inner diameter of the  | Dᵣ     | m    | 0.0625|
| annulus                |        |      |       |
| Height                 | T      | m    | 0.2200|
| Number of Blade        | B      |      | 8     |

**Table 3: Feed Composition**

| Feed composition        | Symbol | Unit   | Value |
|-------------------------|--------|--------|-------|
| Inlet mass flow         | mᵥ     | Kg/s   | 0.0025|
| Feed Density            | ρᵥ     | Kg/m³  | 975   |
| Light component fraction| X.L    |        | 0.8572|
| Thermal light conductivity| k.L | W/m.K | 0.1210|
| Heavy thermal conductivity| k.H | W/m.K | 0.0870|
| Light density           | ρ.L    | Kg/m³  | 823   |
| heavy density           | ρ.H    |        | 975   |
| Light heat capacity     | Cp.L   |        | 2,409 |
| Heavy heat capacity     | Cp.H   |        | 2,734 |

4. Results and Discussion

4.1. The relation between Rotor and Rotation with Heat Transfer Coefficient ($h_r$)

The speed of rotation of the rotor can be modeled by changing the heat transfer coefficient ($U$) that is calculated for corresponding speed. Therefore, the manual calculation is necessary to determine the heat transfer coefficient for each variable of the rotation speed of the rotor. Results are obtained on the graph in Figure 3. Heat transfer coefficient value obtained from the calculation will be used in modeling the thin film evaporator at Aspen Plus software for each variable rotation speed of the rotor.
4.2. Effect of Various Rotor Rotation Vapour Fraction and Vapour Mass Flowrate

Variations of rotor rotation used in this simulation were from 0 up to 60 RPM. Variations of this rotor rotation were simulated to each variable operating temperature of the thin film evaporator at a temperature of 250 °C, 270 °C, 290 °C, 310 °C and 330 °C. Parameters that would be observed are the amount of vapor fraction and composition of the vapor fraction that is carried to the top product. In this case, the operating pressure is in a vacuum of 2.53 kPa. The results of the simulation model of thin film evaporator for various rotor rotations can be seen in Figures 4 and 5. Vapor fraction and mass flow of vapor produced are proportional in general with the speed of rotation. This is true because the equation above, the overall heat transfer coefficient is proportional with rotation speed. The amount of vapor for rotor rotation increases significantly until about 6 RPM then steadily rises until 30 RPM.

4.3. Effect of Various Operating Temperature on Product Composition

Variations in temperature used in this simulation are in the range of 250 °C to 330 °C with increments of 20 °C. Rotation speed also varied in each of these variables. The percentage of lube oil and residue in distillate for each variable and mass flow of lube and residue are plotted in Figures 6, 7, 8, and 9.

Figure 3: Comparison graph between heat transfer coefficient and the rotational speed of the rotor

Figure 4: Graph of Vapor Fraction and Mass Flowrate Against Rotor Rotation at 310°C

Figure 5: Graphs of Vapor Fraction Against Rotor Rotations at Various Temperature
It can be seen in Figure 6, the percentage composition of lube oil in 60 RPM is higher than in 6 RPM when the operating temperature between 250 °C - 310 °C. Above 310 °C, the percentage composition of lube oil in 60 RPM is lower than in 6 RPM. So the highest percentage of lube oil composition is found at a temperature of 310 °C. Below 310 °C, every increase in the operating temperature of the thin film evaporator cause lube oil mass flow to increase significantly according to the Figure 8 and the flow rate of residue also increases but not significant according to the Figure 9, so that the percentage of lube oil increases. So, it can be concluded that the optimum operating conditions of this thin film evaporator at a temperature of 310 °C with the rotation of the rotor 30 RPM.
4.4. Validation Using Manual Calculation

Because of the lack of features of Aspen Plus, the tool is modeled with a combination of the heat exchanger and a flash drum. So it is necessary to validate the simulation results using manual calculation. Results of the validation are presented in Table 4. Based on the results of the calculation using MATLAB and the results of the simulation using Aspen Plus, the error is generated. The error does not exceed 5%, therefore the modeling in Aspen Plus can represent a process in Thin Film Evaporator. Percent error obtained in optimum conditions, a temperature of 310 °C and 30 RPM rotor rotation is at 2.45 %.

4.5. Production Composition of Optimum Condition

The optimum operating conditions are obtained at a temperature of 310 °C with an optimum rotor rotation is at 30 RPM. In such operating conditions, the product obtained has the following composition in Table 5.

| RPM | Top Product Fraction Error Percentage (%) |
|-----|-----------------------------------------|
|     | MATLAB | Aspen Plus |                          |
| 6   | 0.7829  | 0.7486     | 4.38                      |
| 10  | 0.8146  | 0.7854     | 3.59                      |
| 20  | 0.8405  | 0.8176     | 2.73                      |
| 30  | 0.8460  | 0.8253     | 2.45                      |
| 40  | 0.8484  | 0.8268     | 2.55                      |
| 54  | 0.8436  | 0.8265     | 2.55                      |
| 60  | 0.8492  | 0.8265     | 2.67                      |
| Average error | 2.98 |

Table 4: Comparison of Simulation Results Thin Film Evaporator Using Aspen Plus and Matlab Operating temperature 310 °C

| Component | Mass flowrate (kg / h) | Mass Percentage (%) |
|-----------|------------------------|---------------------|
| Light End | 0.0001                 | 0.00                |
| Gas Oil | 0.6751                 | 10.00               |
| Lube Oil | 5.7667                 | 85.40               |
| Residue | 0.3110                 | 4.61                |
| Total    | 6.7529                 | 100.00              |

Table 5: Product Composition At Optimum Condition

5. Conclusion

Based on the results of the research that has been done, it can be concluded that the relation between operating temperature and rotor rotation thin film evaporator to the vapor fraction produced is directly proportional. The higher the operating temperature and rotor rotation of Thin Film Evaporator, the higher the vapor fraction generated. But for rotor rotation above 30 RPM, the increase is almost negligible. The optimum operating conditions for this process is at the rotation speed of 30 RPM and 310 °C operating temperature, which produces a vapor fraction of 0.8253 with the percentage of lube oil fractions of 85.40 % to the product and the product mass of 6.75 kg/h.
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References
[1] Querino M V, Marangoni C and Machado R 2018 Chem. Eng. Trans. 69 679-84
[2] Rossi F, Corbeta M, Geraci D, Pirola C and Manenti F 2015 Chem. Eng. Trans. 43 1429-34
[3] Speight J and Exall D 2014 Handbook of Refining Used Lube Oils, CRC Press
[4] Carlo G L 2013 Presentation of Study Tecnologie Progetti Srl
[5] Dziak J 2011 Advanced Topics in Mass Transfer Prof. Mohamed El-Amin (Ed.), INTECH.
[6] Pawar B S, Patil R and Mujumdar U S 2011 Drying Technol. 29 719-28