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Simulation of crude palm oil dilution and clarification in a palm oil mill using computational fluid dynamics: Grid dependency and parametric studies

A H Mohammad Fauzi[1,2], M N A A Saifuddin[1,2], F H Kasim[1,2*] and Z Y Zakaria[3]

[1]Centre of Excellence for Biomass Engineering, Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kompleks Pusat Pengajian Jejawi 3, Kawasan Perindustrian Jejawi, 02600, Arau, Perlis, Malaysia
[2]Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kompleks Pusat Pengajian Jejawi 3, Kawasan Perindustrian Jejawi, 02600 Arau, Perlis, Malaysia
[3]Department of Chemical Engineering, Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

*E-mail: farizul@unimap.edu.my

Abstract. Oil extraction rate (OER) is a useful tool for assessing the performance of palm oil mills, where a higher OER is favorable. The OER can be enhanced by improving the quantity of palm oil recovered from fresh fruit bunches processed. In this study, the simulation of dilution and clarification of crude palm oil (CPO) in a clarifier of a palm oil mill was performed using computational fluid dynamics (CFD) approach. Grid dependency and parametric studies were conducted on the fluid region inside the clarifier. From the results, the utilization of medium-sized mesh managed to achieve grid-independent solutions, with the average percentage error of 12.4% based on the comparison of the actual and simulation data. Moreover, the input parameters (i.e., velocity, temperature, and oil mass fraction of the inlet) significantly influenced the oil mass fraction of the outlet based on the coefficient determination (R^2) values. As a conclusion, CFD has the potential to enhance the OER of a palm oil mill by enabling the study of parameters influencing dilution and clarification of CPO without the need of conducting experiments.

1. Introduction

Palm oil is the most versatile oil as it can be used in various food applications and non-food products without or with only minimal modifications. Due to its unique properties, there is a high demand for palm oil throughout the world. Malaysia was the second largest producer of palm oil after Indonesia based on the data for the world supply and distribution of palm oil in 2019 [1]. Furthermore, in 2019, Malaysia recorded an increase of 1.8% of crude palm oil (CPO) production compared to the previous year, as well as an increase of 12.0% of the total palm oil exported [2]. This highlights the significance of palm oil to Malaysia, which is one of the most important commodities for the country.

Oil extraction rate (OER) is the percentage of the weight of oil physically removed from a known weight of fresh fruit bunches (FFBs) processed [3]. The OER is useful to assess the quantity of CPO produced, where a higher OER is favorable for palm oil mills. In order to increase the OER, the amount of oil recovered should be high over the FFB processed, based on Equation 1:

$$OER = \frac{Oil\ Recovered}{FFB\ Processed} \times 100\% \quad (1)$$

The importance of OER is highlighted by the inclusion of OER under the 12 National Key Economic Areas (NKEAs) introduced as part of Malaysia's National Transformation Program [4]. For the palm oil and rubber area, the Entry Point Project (EPP) related to OER is to increase OER from 20.5% in 2009 to 23.0% by 2020 [5]. This objective is achievable by using OER as a management tool in assessing the performance of a mill and plantation. The national OER in 2019 was 20.21% [2]. Therefore, feasible strategies need to be formulated in order to meet the targeted OER.

Wet palm oil milling is the most common method used to extract palm oil. After the extraction of palm oil from FFBs, water is added for the separation of CPO from other components, such as debris, sand, and non-oily solids. Dilution and clarification are vital processes in wet palm oil milling. Both processes are closely related to OER. In dilution, diluted crude oil (DCO) is produced after hot water is added to undiluted crude oil (UCO). Meanwhile, CPO is obtained via clarification after it is separated from solid impurities in a clarifier. Various parameters influence these processes, such as the inlet velocity, temperature, oil mass fraction, and others. Improving dilution and clarification in palm oil mills is difficult by considering the cost and raw materials involved. Thus, a feasible approach is needed for improving dilution and clarification in a palm oil mill.

Computational fluid dynamics (CFD) can simulate flow conditions without the need to conduct experiments that are time-consuming and costly. By solving mathematical equations governing the fluid flow of a process, CFD allows researchers to observe the parameters in processes without conducting experiments. Several studies have been conducted to examine the performance of clarifiers in different industries using CFD for better understanding of the fluid flow behavior in clarifiers. These include studies in wastewater treatment [6, 7] and sugar production [8, 9]. Nevertheless, no study has been performed on clarifiers in palm oil mills.

In this study, the CFD approach was carried out for simulating dilution and clarification of CPO in a clarifier of a palm oil mill. The approach was chosen to avoid the need of conducting experiments regarding dilution and clarification at the palm oil mill. The parameter for dilution was represented by the oil mass fraction at the inlet ($\%Oil_{inlet}$), whereas the parameters for clarification were represented by the inlet flow velocity (v) and the temperature of the clarifier (T). The oil mass fraction of the outlet pipe ($\%Oil_{outlet}$) for the clarifier was determined from the simulation for the comparison between numerical (i.e., CFD) and experimental (i.e., data from the palm oil mill) values. The aim of the simulation was to minimize $\%Oil_{outlet}$ so that the loss of palm oil in the underflow of the clarifier can be minimized and CPO production can be improved. Furthermore, the influence of varying inlet parameters was also evaluated.

2. Methodology

2.1. Collection of industrial data

The industrial data for the study were collected from a palm oil mill in Kampung Gajah, Perak with the permission from the mill's management. Among the data required for CFD simulation include the dimensions of the clarifier with inlet and outlet pipes (i.e., height, diameter), process parameters (i.e., v, T, $\%Oil_{inlet}$, and $\%Oil_{outlet}$), and other related data (i.e., FFB processed, CPO produced, and OERs).

2.2. Simulation of the clarifier

This phase involves CFD simulation of a clarifier using ANSYS software. The main steps in the simulation are geometry creation and meshing, physics definition and boundary conditions, simulation (solver), and validation.

2.2.1. Geometry creation and meshing. In this step, the geometry of the clarifier was drawn based on the dimensions obtained from the industrial data using ANSYS DesignModeler. The geometry represents the fluid flow region being studied, as well as the computational domain of the clarifier, where only the flow of the fluid inside the clarifier was considered. The exact dimensions of the clarifier defined the boundaries of the geometry (i.e., 1:1 scale), which are equivalent to the effective volume of the process. After the clarifier was drawn, the meshing of the physical model was performed using ANSYS Meshing for the discretization of the domain. Figure 1 shows the geometry sketch of the clarifier after meshing. Coarse, medium, and fine meshes were applied for the grid dependency study. Tetrahedral elements were selected for this study. This is because comparatively fewer elements are needed compared to quadrilateral/hexahedral elements when considering a complex geometry [10].

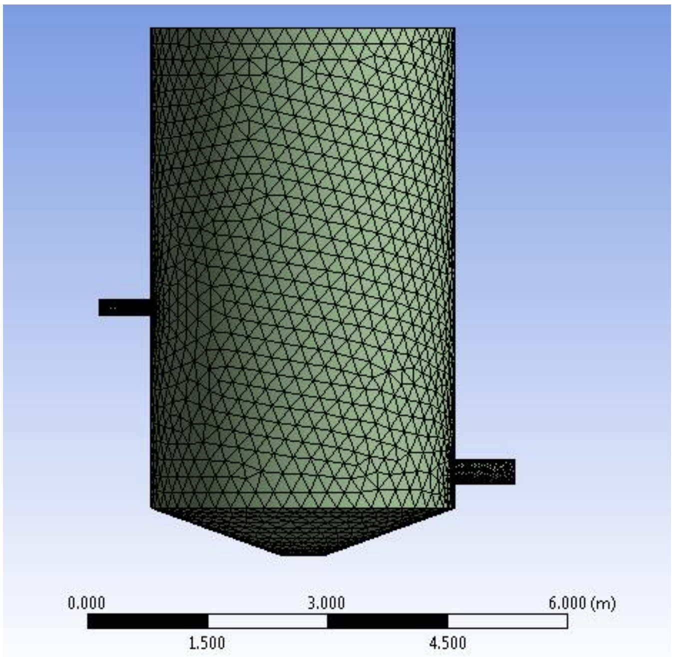

Figure 1. Geometry sketch of the clarifier after meshing.

2.2.2. Physics definition and boundary conditions. After meshing, the model was exported to ANSYS Fluent for the simulation of the clarifier. Table 1 presents the setup used in the CFD solver. The Eulerian model was selected to represent the multiphase condition of this study, where two phases were involved due to the immiscibility of palm oil and water. Moreover, as the volume fraction of the dispersed phase (i.e., palm oil) exceeded 10%, thus the Eulerian model was preferred than the Volume of Fraction model [10]. Due to the intermittent and irregular flow inside the clarifier of a palm oil mill, the standard k-ε (two-equation) model was selected as the turbulence model. At the inlet pipe, the initial condition values used the data collected from the palm oil mill (i.e., v, T, and $\%Oil_{inlet}$), as shown in Table 1. Meanwhile, for the outlet pipe, the pressure outlet boundary condition was implemented.

Table 1. CFD solver setup.

Settings	
Multiphase model	
Model	Eulerian
Number of Eulerian phases	2
Viscous model	
Model	Standard k-ε (two-equation)
Near-wall treatment	Standard wall functions
Operating conditions (inlet)	
Pressure (Pa)	101,325
v (m/s)	0.439–0.495
T (°C)	70–92
$\%Oil_{inlet}$	32%–36%
Solution domain	
Pressure-velocity coupling	Coupled
Gradient	Least squares cell based
Momentum	Second order upwind
Volume fraction	QUICK

2.2.3. Simulation (solver). In this study, the transient simulation method was applied due to the turbulence nature of the fluid inside the clarifier. The residual values were set at 10^{-4} for all variables. These values are important for judging convergence of the simulation. Furthermore, the palm oil fraction at the outlet pipe was monitored using the surface monitor function of ANSYS Fluent.

2.3. Grid dependency and parametric studies
The grid dependency study was performed to eliminate errors due to the coarseness of the grid. The clarifier was meshed into three different relevance centers (i.e., coarse, medium, and fine) to determine the effect of the overall grid resolution on the prediction of the model. In the parametric study, the influence of different boundary conditions of the clarification of CPO was investigated. A series of simulation were conducted by varying the values of input parameters to observe their influence on the oil mass fraction at the outlet.

3. Results and discussion
3.1. Grid dependency study
The results from the simulation were compared with the experimental data as a reference to determine the most suitable mesh for the simulation of CPO dilution and clarification. The runs for each mesh were averaged and the average percentage of error was determined. Table 2 shows the average percentage error for coarse, medium, and fine mesh sizes of the clarifier. Although the simulation for fine mesh showed greater accuracy in terms of simulation performance, the low percentage or error and fast turnover is more desirable to reduce simulation time. This is because the study on various boundary

conditions influences the convergence rate of each simulation run. Meanwhile, Table 3 presents the comparison between the actual and simulation data for the dilution and clarification of CPO using medium-sized mesh. From the results, there was not much difference in the percentage of error between the actual and simulation data. Therefore, the solutions from the medium mesh were considered to be grid-independent.

Table 2. Details of the meshes used in the grid dependency study.

Mesh Size	Element	Number of Cells	Average Error (%)
Coarse	Tetrahedral	229,739	20.5
Medium	Tetrahedral	246,797	12.4
Fine	Tetrahedral	338,144	11.8

Table 3. Comparison between actual and simulation data for dilution and clarification of crude palm oil.

Run	$\%Oil_{outlet,actual}$	$\%Oil_{outlet,CFD}$	Error (%)
1	4.00%	4.44%	11.1
2	4.00%	4.60%	14.9
3	6.00%	5.35%	10.8
4	4.00%	4.43%	10.7
5	4.00%	4.49%	12.3
6	6.00%	5.36%	10.6
7	6.00%	6.58%	9.6
8	4.00%	4.52%	13.1
9	4.00%	4.47%	11.6
10	4.00%	4.58%	14.4
11	4.00%	4.55%	13.7
12	4.00%	4.57%	14.3
13	6.00%	6.80%	13.3
14	4.00%	4.51%	12.7
15	6.00%	5.28%	12.0
		Average	12.4

3.2. Parametric study of CPO dilution and clarification

A series of simulation was carried out by varying the inlet parameters (i.e., v, T, and $\%Oil_{inlet}$). The influence of the parameters on the oil mass fraction was evaluated. The aim of the parametric study was to minimize $\%Oil_{outlet}$ in the underflow of the clarifier.

3.2.1. Effect of temperature. The v and $\%Oil_{inlet}$ were set at 0.47 m/s and 35%, respectively. Meanwhile, the range of the T was varied from 60 to 100 °C. The plot of $\%Oil_{outlet}$ against T is presented in Figure 2. The values of $\%Oil_{outlet}$ decreased with T. This means that a higher temperature is desirable to obtain a lower $\%Oil_{outlet}$.

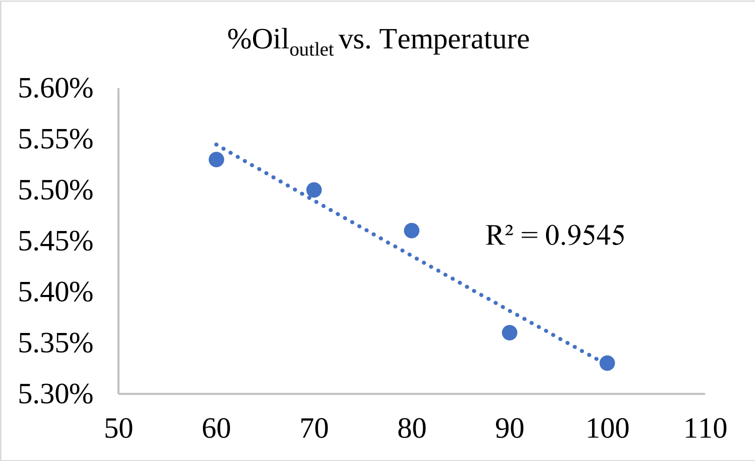

Figure 2. Effect of temperature at the inlet on $\%Oil_{outlet}$.

3.2.2. Effect of inlet velocity. The T and $\%Oil_{inlet}$ were set at 80 °C and 35%, respectively. Meanwhile, the range of v was varied from 0.37 to 0.57 m/s. The plot of $\%Oil_{outlet}$ against v is presented in Figure 3. The values of $\%Oil_{outlet}$ decreased with v. This means that a higher velocity is desirable to obtain a lower $\%Oil_{outlet}$.

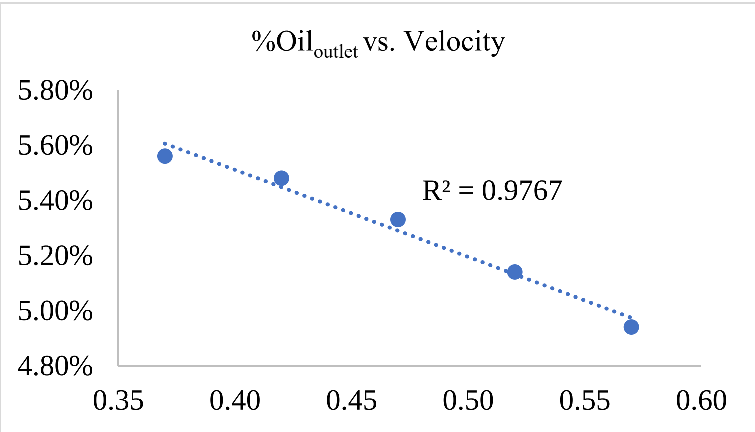

Figure 3. Effect of inlet velocity at the inlet on $\%Oil_{outlet}$.

3.2.3. Effect of inlet oil mass fraction. The T and v were set at 80 °C and 0.47 m/s, respectively. Meanwhile, the range of $\%Oil_{inlet}$ was varied from 31% to 39%. The plot of $\%Oil_{outlet}$ against $\%Oil_{inlet}$ is presented in Figure 4. The values of $\%Oil_{outlet}$ increased with $\%Oil_{inlet}$. This means that a lower oil mass fraction at the inlet is desirable to obtain a lower $\%Oil_{outlet}$.

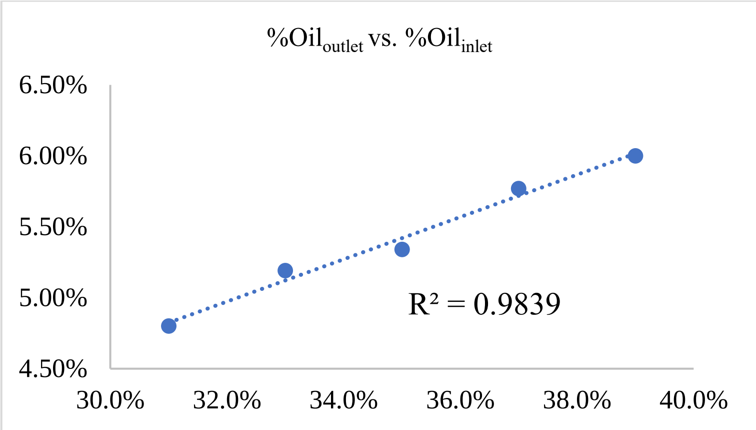

Figure 4. Effect of oil mass fraction at the inlet on $\%Oil_{outlet}$.

4. Conclusion

Computational fluid dynamics was successfully used for the simulation of dilution and clarification in a clarifier of a palm oil mill. The aim of the study was to minimize $\%Oil_{outlet}$ in the underflow of the clarifier for improving OER. Grid-independent solutions were achieved by applying medium-sized mesh, with the average percentage error of 12.4% based on the comparison of actual and simulation data. The results showed that the increase of T and v of the inlet flow reduced the $\%Oil_{outlet}$, whereas the increase of $\%Oil_{inlet}$ increased the $\%Oil_{outlet}$. All input parameters significantly influenced the $\%Oil_{outlet}$ based on the R^2 values for each input parameter. In conclusion, CFD can provide a better understanding of the processes in a clarifier, where the effect of input parameters can be determined without the need of conducting experiments using a clarifier. Therefore, CFD has the potential to improve the OER of a palm oil mill where only the data from the palm oil mill are needed.

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