



Simulation of an Extractor for the Extraction of Vegetable Oil from Palm Kernel

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To cite this article:

Akpa Jackson Gonurubon, Dagde Kekpugile Kenneth, Afolayan Joel Tobi, Adeloye Olalekan Michael. Simulation of an Extractor for the Extraction of Vegetable Oil from Palm Kernel. *American Journal of Chemical and Biochemical Engineering*. Vol. 5, No. 2, 2021, pp. 41-48. doi: 10.11648/j.ajcbe.20210502.11

Received: August 9, 2021; **Accepted:** August 20, 2021; **Published:** August 31, 2021

Abstract: Industrial production of vegetable oil from palm kernel seed operational process was analysed in this research study with the extractor unit as the main focus of the study. The extractor unit consist of nine operational stages, which was modeled by applying the principle of the law of conservation of mass and energy respectively. The developed models were a set of ordinary differential equations, which were solved by using MatLab ODE 45 solver by applying industrial extractor plant data of Vegetable Oil Production Company. The developed models' results were compared with the industrial extractor plant data in terms of mass fraction of oil and temperature of the raffinate and mass fraction of oil and temperature of the extract and these yielded an absolute percentage error (deviation) of 7.0, 9.52, 3.29 and 2.29 respectively. Thus, the deviations are within the acceptable limits, which shows that the developed models predicts adequately the extraction process of vegetable oil production. In addition, the effects of mass flow rates of raffinate and extraction solvent were studied with increase in mass flow rate of raffinate reduces contact time between extraction solvent and the cake thereby reducing the efficiency of the extraction process with maximum amount of oil been extracted at the minimum flow rate of 300Kg/hr.

Keywords: Extractor unit, Raffinate (Cake), Extract (Miscella), Counter Current Mode, Extraction Solvent, MatLab ODE45

1. Introduction

Extraction is a long age method of separation used in the chemical industry for the separation of one constituent from the other by reason of their difference in solubility. Extraction can also be defined as a chemical process which involves the removal of a constituent component from its source which is of paramount importance to the individual involved [1] Main sources of plant oil for commercial purposes that contain edible oils are soybean, sunflower, groundnuts, rapeseed, coconut, oil palm etc [2]. Also, there are extractible oils in many plants that are useful either as food or cosmetic formulations for centuries [3]. In recent time, some oil bearing plants are sources of renewable energy especially in bio-diesel fuel production by researchers [4]. The composition of oil in seeds such as

oleaginous, nut, kernel, or fruit pulps is from 3% to 70% of the total weight and chemical structures akin to animal fats [5]. The importance of oilseed processing and sales to individual or grouped farmers, companies, and even to national economies are enormous due to its main products oils and meal or cake, which are of both great commercial value. Developing nations such as Malaysia, Cameroon, and Ivory Coast have a great sections of population whose livelihoods mainly depend on palm oil processing and sale. Statistically, the production of vegetable oil worldwide has increased steadily from about 90.5 million metric tons in 2000/2001 to 207.5 million metric tons in 2019/2020 and with expected future growth trend [6]. It has been known for centuries that various techniques have been applied in extracting oil from its oilseeds, and the main objective of these extraction techniques is in optimizing operational process by extracting or removing the optimum amount of oil in oilseeds at least or

minimum operational costs. The tissues of plants bear varying quantities of vegetable oils [7]. Extraction of vegetable oil from its source such as palm kernel is usually done in two major ways either mechanically (expelled method) or chemically by (solvent extraction). In the expelled method the solid particles are squeezed with specially design machine (extractor) to release the oil. However, this method leaves about 5-7% oil in the cake [8]. In the solvent extraction process, the solid particles is allowed to mix with the solvent which forms a homogenous liquid with the oil, this homogenous liquid is then separated to recover oil and the used solvent. This process of oil extraction leaves 1.0-1.5% oil in the cake and has a high extractability tendency than the expeller method. The solvent commonly used in the solvent extraction process is either hexane or Straight Run Gasoline (SRG) [9]. In addition, extraction techniques for the more conventional oilseeds are known, researchers have continued in their quest in improving overall yields of extraction process. One proper way of improving extraction yields is to analyse the extraction process, thereby evaluating the variation of process products (raffinate and extract) with the process condition of the extraction method, as these will assist in studying production trend and simulating the extraction process yield with respect to operational conditions [10]. The parameters used to predict the performance of an oil extraction system include Extraction Yield, Extraction Efficiency and Extraction Loss [11].

- 1) Extraction Yield: Extraction yield is the amount of oil derived from a certain quantity of oleaginous material in a certain extraction process, expressed as a percentage.
- 2) Extraction Efficiency: Extraction efficiency refers to the ratio of the quantity of oil extracted to the amount of oil present in the oleaginous material, expressed as a percentage.
- 3) Extraction Loss: Extraction loss is expressed as the weight of material that cannot be accounted for at the end of the extraction operation, either as oil recovered or the residual cake, usually described as a percentage of the total weight of material before extraction.

Also, the main process that take place in an extraction process includes seed-in-take, preparatory process and extraction process. The seed-in-take is where the seeds are received and removed from unwanted impurities then stored for processing. The Preparatory process is the second stage of the extraction process and involves size reduction operation where increase in surface area for increase in extractability is achieved. The machine normally used for the preparatory plant is the size reducing machines such as harmer mill and breaker. There are also conveyors for transporting of the raw material (palm kernel). Finally is the extraction section where the oil is extracted from its source such as palm kernel with the help of a solvent to form a homogenous liquid with the oil [12]. Thus, this research study developed models that predicts the amount of oil extracted from its raw material (palm kernel) in an extractor by performing mass balance on the extractor to determine the rate at which solute-solvent (miscella) is separated from the particles by applying the principle of conservation of mass, carry out energy balance analysis on the extractor to evaluate temperature change as the extractor process occurs from stage to stage through the

application of the principle of conservation of energy, solved the developed models using MatLab ODE45 solver and simulation of the solved models using industrial vegetable oil company data to study the effects or variations of certain process variables on the extraction process.

2. Raw Materials Preparation

The major raw material used in this process is palm kernel which is obtained through vendors that supply the kernels. The supplied kernel are first powered into a horizontal screen vibrator where impurities such as shells, shafts and iron particles are removed then transported to silos for storage via screw conveyors and elevators. The kernel from the silo enters the hammer mill where they are crushed. The crushed kernels are filtered with the aid of filters placed under the rotary disc of the hammer mill. The filtered crushed kernel moves to the beaker where it is further reduced in size. The reduced material from the beakers moves to the flaker, where they are made into flakes which are flat material with relatively increased surface area [13]. The leaching mechanism may include simple physical solution or dissolution that are possible by chemical reaction. The transport rate of solvent into the mass to be leached, or of soluble fraction into the extraction solvent from the insoluble material, or combinations of these rates are very important and may involve a membranous resistance. Furthermore, the vrate of chemical reaction also affects leaching rate [14]. The extraction technique applied depends on the proportion of soluble constituent present, its distribution throughout the solid, the nature of the solid and the particle size. Therefore, for uniformly dispersed solute in the solid, the surface nearby material are dissolved first, reaching a porous structure in the solid reside. The solvent penetrates this outer layer before it reaches further solute, and the process becomes progressively more difficult, leading to reduction in the extraction rate. If the solute, the porous structure may break down almost immediately to give a fine deposit of insoluble residue and access of solvent to the solute will not be impeded. Generally, the process can be considered in three parts.

- 1) Phase change of solute as dissolution in solvent occurs.
- 2) Diffusion via the solvent in the solid pores to the outside of the particle.
- 3) The transfer of the solute from the solution in contract with the particles of the main bulk of the solution.

The extraction process or rate could be limited by one of these three process via phase change of the solute as solvent dissolution occurs so rapidly with a negligible effect on the overall rate [15].

Furthermore, the factors that are responsible for limiting the rate of extraction also influences equipments selection for an extraction process. Hence, if residual solid diffusion is the controlling factor, small size material should be applied so that the solute travels small distance. There are six important factors to be considered [16].

- 1) Particle Size: The rate of extraction is affected or influenced in several ways by particle size. The smaller particle size yields greater interfacial area between the

solid and liquid, and thus, the transfer rate of material is higher and the smaller is the distance the solute must diffuse within the solid as already indicated. It is therefore desirable that the particles size range should be small so that each particle requires approximately the same extraction time. In particular, the production of a large amount of fine material should be avoided.

- 2) Extraction Time: The degree of extraction is influenced by extraction time, which depends on the nature and structure of the extraction material.
- 3) Solvent: A good selective solvent should be chosen with its viscosity sufficiently low for free circulation. In generally, a relatively pure solvent will be applied initially but as the extraction progresses, solute concentration will increase and the extraction rate will progressively decline due to reduction in concentration gradient and solution becoming more viscous.
- 4) Temperature: The solubility of the extracted material increases with temperature thereby yielding a higher extraction rate. Studies have shown that ambient temperature equilibrium, hexane extraction of palm kernel produced equal quantity of oil as was extracted from the flakes by conventional high temperature processing, the ambient temperature extracted oil contained less phospholipids than commercial crude oils obtained by traditional processing. The coefficient of diffusion is expected to increase with rise in temperature, thereby improving the rate of extraction.

3. Material and Method

The materials applied in this extraction research study include nine extraction stages, extraction solvent, crushed kernel, mass balance, energy balance, operating data, MatLab software etc.

3.1. Process Description

In the extraction of vegetable oil, there are three processes involved namely extraction, distillation and cooling, and this research focuses on the extraction part of the process. In order to analyze the behaviour of a chemical process, a mathematical representation of the physical and chemical phenomena taking

place in the process is required. Such a mathematical representation constitutes the model of the system. The process occurring in the extractor is mass transfer of the oil from the crushed kernel to the solvent. The modeling of the extractor will therefore be based on the equations describing this phenomenon. These equations are the continuity equations for the transfer of mass and energy (heat). In addition, the extractor consists of N stages and each stage being a distinct tank. The crushed kernel contains transferable material oil which is to be extracted using the solvent (hexane). For each stage N , R moles of raffinate solvent from stage $N-1$, containing X_{n-1} moles of A per mole of solvent, is charged in along with E moles of extract solvent from stage $n+1$, containing Y_{n+1} moles of A per mole of solvent. After attaining of equilibrium in stage n , the raffinate is sent to stage $n+1$ and extract to stage $n-1$ and the procedure repeated in the other stages. (Initially R moles of Solvent with composition Y_0 (Moles A per mole of solvent) were charged into tank 1 and the extract, E moles of solvent with composition X_{n+1} moles of A per mole of solvent were charged into tank N to start the process. After the initial start-off period, the condition in the process conforms to a counter-current scheme (Figure 1) and the principle of conservation of mass and energy will be applied to stage n of this process to develop a mathematical model that can predict the flow of mass and energy (temperature) in and out of the extractor.

3.2. Extractor Model Equations

The extractor model equation predicts the behaviour of the extractor such that important extraction components and variables are evaluated. These model equations were developed from first principle by applying the law of conservation of mass and energy with the following assumptions of constant coefficient of extraction throughout the N th extraction stages, no axial dispersion (no turbulent and droplet sizes difference that lowers process efficiency), an adiabatic extraction process (well insulated for minimum heat transfer), phase and thermal equilibrium in each stage of the extractor (no variation in components and flow rates), constant holdup in extract and raffinate phases and no chemical reaction taking place in the extraction process.

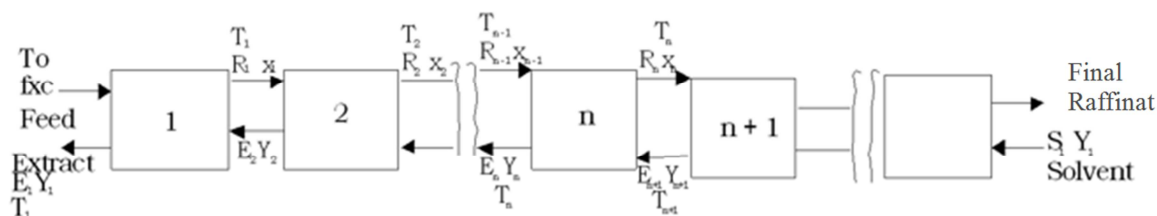


Figure 1. Nth stage Extraction Process.

The principle of conservation of mass was applied in developing the model by taking a balance on N th stage extractor. Since the extract (miscella) and raffinate (cake) solution are in equilibrium with each other for all the stages, the concentration of the solute (oil) in the two streams is thus

represented by the distribution equation.

$$Y_N = KX_N \quad (1)$$

Hence with reference to the above assumptions, the extractor model equation predicting the amount of oil in the

raffinate with time is expressed as.

$$\frac{dX_N}{dt} = \left(\frac{R_{N-1}}{Kh+H}\right)X_{N-1} - \left(\frac{KE_N+R_N}{Kh+H}\right)X_N + \left(\frac{KE_{N+1}}{Kh+H}\right)X_{N+1} \quad (2)$$

Defining terms in the extractor mass balance model equation and substitution into the equation yields.

$$\frac{dX_N}{dt} = a_0X_{N-1} + a_1X_N + a_2X_{N+1} \quad (3)$$

$$\frac{dT_N}{dt} = \left(\frac{R_{N-1}X_{N-1}}{(Kh+H)X_N}\right)T_{N-1} - \left(\frac{(E_{N+1}KX_{N+1}+R_{N-1}X_{N-1})}{(Kh+H)X_N}\right)T_N + \left(\frac{E_{N+1}KX_{N+1}}{(Kh+H)X_N}\right)T_{N+1} \quad (4)$$

Similarly, the extractor energy balance model equation showing temperature variation with time can be expressed as

$$\frac{dT_N}{dt} = b_0T_{N-1} + b_1T_N + b_2T_{N+1} \quad (5)$$

Thus, Equations (2) and (4) constitutes the mathematical models of the Nth stage extractor.

Also, the model equations for the nine stages of the extraction process that predicts the amount of oil in the raffinate (cake) and the temperature progression of the extractor with time can be written in matrix form from Equations (3) and (5) as follows.

1) Extractor Mass Balance Equation

$$\frac{d}{dt} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_0 & a_1 & a_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_0 & a_1 & a_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_0 & a_1 & a_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_0 & a_1 & a_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_0 & a_1 & a_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_0 & a_1 & a_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_0 & a_1 & a_2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_0 & a_1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \end{bmatrix} + \begin{bmatrix} a_0x_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ a_2x_{10} \end{bmatrix}$$

2) Extractor Energy Balance Equation

Similarly, the principle of the conservation of energy was applied to determine the energy balance model equation, which predicts the temperature distribution in the Nth stage extractor process. Hence, for a non-reacting extraction process, the energy balance model equation based on the assumptions stated above yields.

$$\frac{d}{dt} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \end{bmatrix} = \begin{bmatrix} b_1 & b_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ b_0 & b_1 & b_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_0 & b_1 & b_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & b_0 & b_1 & b_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b_0 & b_1 & b_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & b_0 & b_1 & b_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & b_0 & b_1 & b_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_0 & b_1 & b_2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & b_0 & b_1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \end{bmatrix} + \begin{bmatrix} b_0T_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ b_2T_{10} \end{bmatrix}$$

3.3. Solution Technique

The model equations developed for the extraction process from the first principle yielded a system of first order linear ordinary differential equations, which will be solved using MatLab ODE45 solver. In addition, these models will be validated by using industrial extractor production data to test for the suitability of the model in predicting the amount of oil left in the raffinate (cake) and the oil extracted from the cake in the extract (miscella) at the end of the extraction process. Hence, a simulation analysis of the developed models was performed to study the effect of process variables on the extraction process.

Table 1. Comparison of Model Prediction and Plant Data.

Parameter	Plant Data	Model Prediction	Percent Deviation
Mass Fraction of Oil in the Raffinate (Cake)	0.30	0.321	-7.0
Mass Fraction of Oil in the Extract (Miscella)	0.70	0.723	-3.29
Temperature of the Raffinate	110	120.47	-9.52
Temperature of the Extract	55	56.26	-2.29

4. Result and Discussion

The results obtained after solving the developed model equations for extraction process are presented thus.

4.1. Model Validation

The comparison of the developed model results for extraction process with the industrial extraction production data are presented in Table 1.

Thus, the mass fraction of oil in the raffinate (cake), the extract and the outlet temperature of both the raffinate and the extract as predicted by the developed model using

industrial data is in tandem with the mass fraction of oil in the raffinate, the extract and the outlet temperature of the raffinate and extract of an industrial extractor data with deviations or minimum absolute error ranging from 2.29 to 9.52 percent.

4.2. Model Results

The results deduced from the developed models to predict the amount of oil in the raffinate (cake) and extract (miscella) and the outlet temperature of the raffinate and extract in a nine stage extraction process are discussed thus.

4.2.1. Mass Fraction Oil in the Raffinate

In the extraction process, a pure solvent (hexane) is used to

extract oil from crushed kernel (flakes), and on contact with the flakes, the solvent extracts the oil. The initial rate of extraction is very high since the extraction solvent is pure, however as the oil is extracted, it mixes with the solvent and

the density of the resulting mixture increases resulting in a decrease in the rate of extraction. Hence, there is an increase in the amount of oil in the solvent and a decrease in the amount of oil in the flakes (cake) with time.

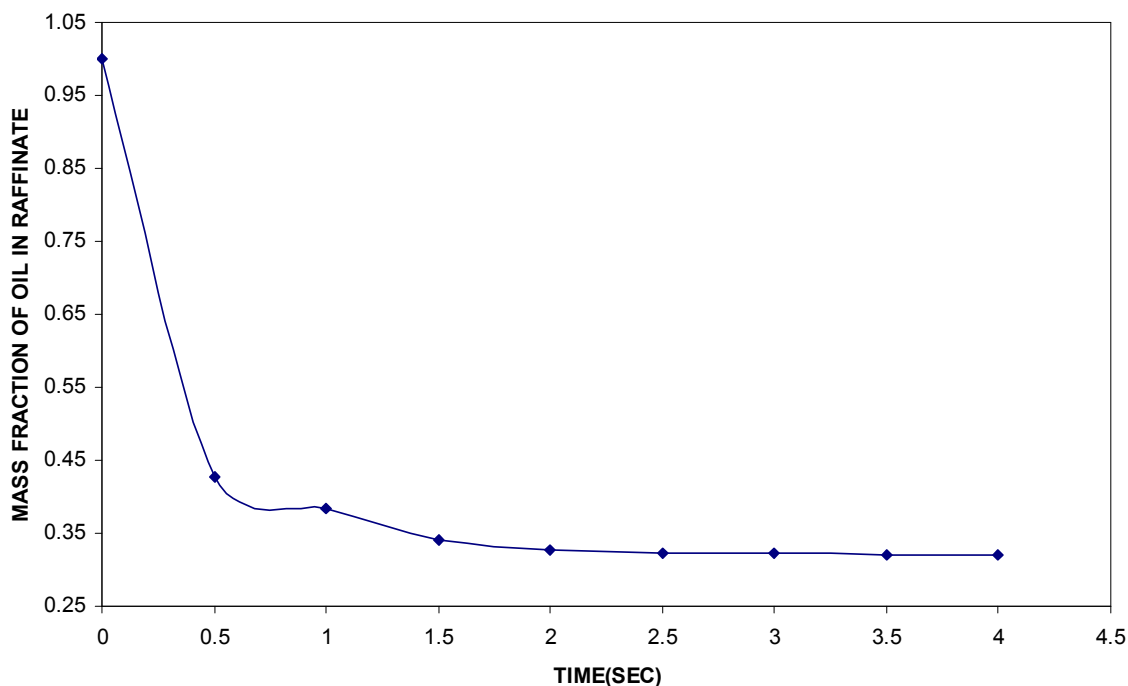


Figure 2. Mass Fraction of Oil in the Raffinate Phase with Time.

4.2.2. Mass Fraction Oil in the Extract

The developed model prediction for the extract phase is shown in Figure 3, which shows an instantaneous decrease and increase in the amount of oil extracted from the cake and

in the solvent at the beginning of the extraction. However, as the extraction process continued there is a gradual reduction in the rate of extraction.

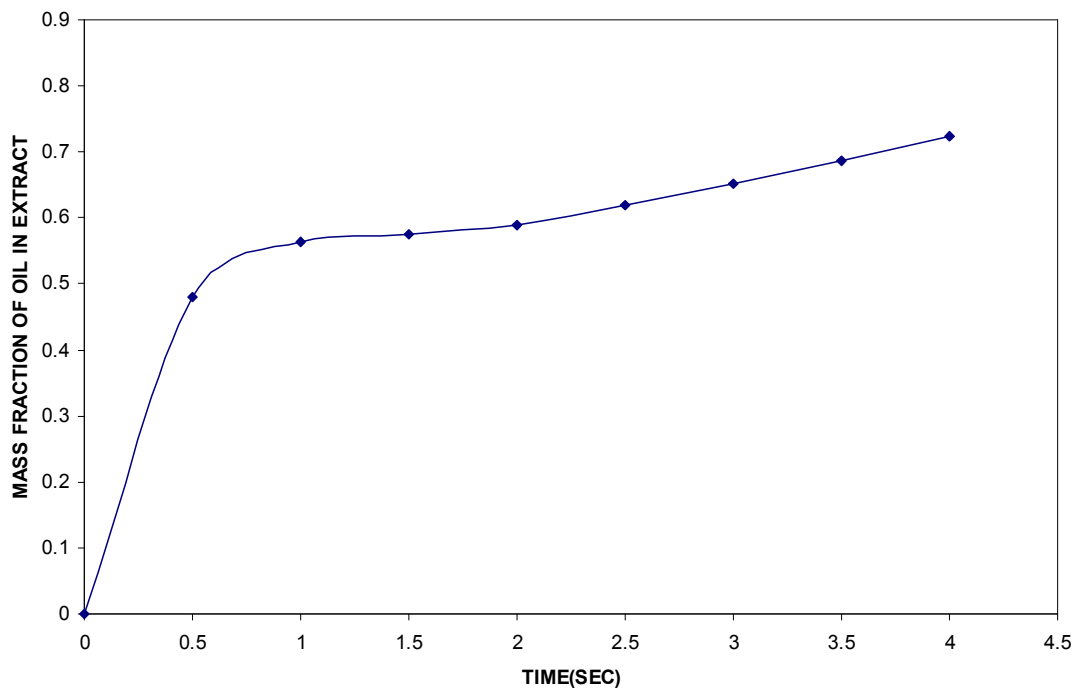


Figure 3. Mass Fraction of Oil in the Extract with Time.

4.2.3. Outlet Temperature of Extract and Raffinate

The developed models also predicts a steady increase in the outlet temperature of extract and raffinate with time, due

to the heat exchanged between the cake and steam at the outlet of the extractor as depicted in Figure 3 and Figure 4 for extract and raffinate respectively.

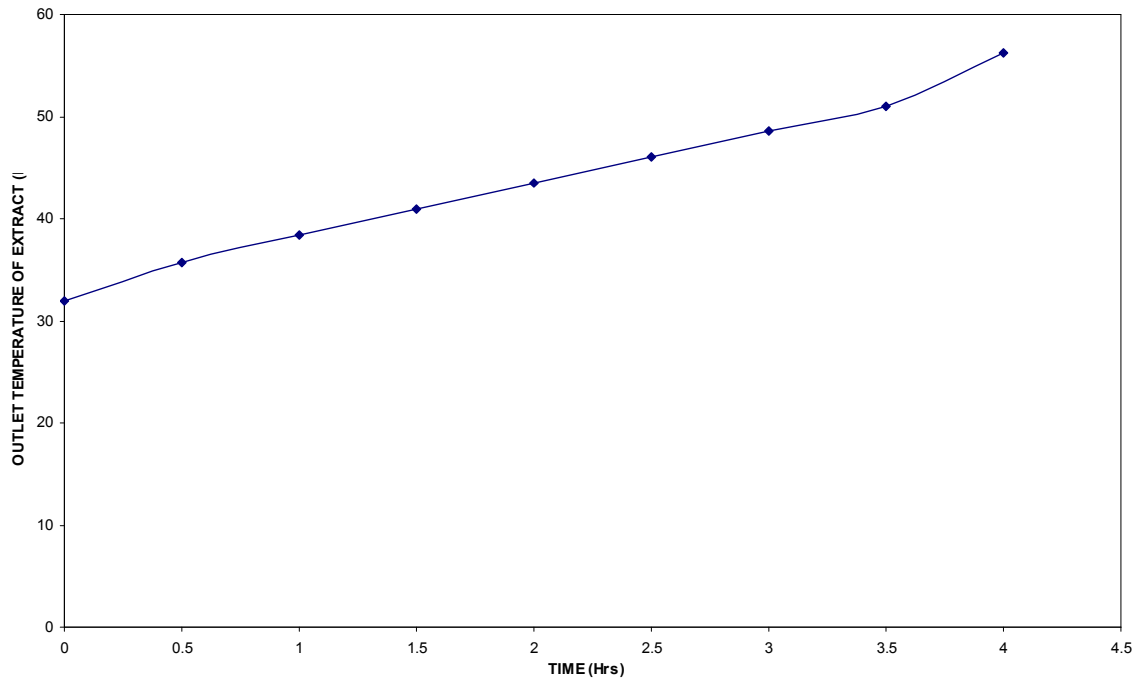


Figure 4. Outlet Temperature of Extract with Time.

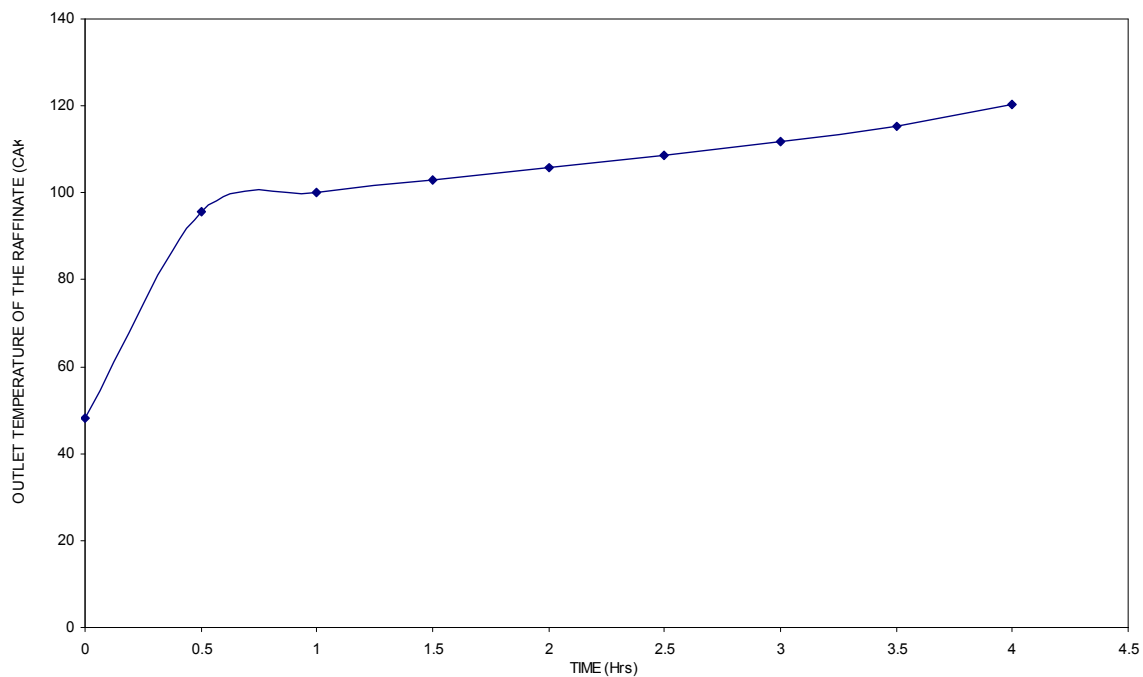


Figure 5. Outlet Temperature of the Raffinate (cake).

4.3. Model Simulation

The simulation model is useful in optimizing plant performance by setting the optimal value of operating condition. However before optimizing, it is important to determine how sensitive a process is with the decision variables. Therefore, sensitivity analysis is carried out to

evaluate certain process variables effects on the performance of the developed models.

4.3.1. Mass Flow Rate of the Raffinate

The effects of the mass flow rate of the raffinate on the amount of extracted and amount of oil in the cake, showed an increase in the mass flow rate of the raffinate reduces the

contact time between the solvent and the cake which leads to poor extraction of the oil from the cake

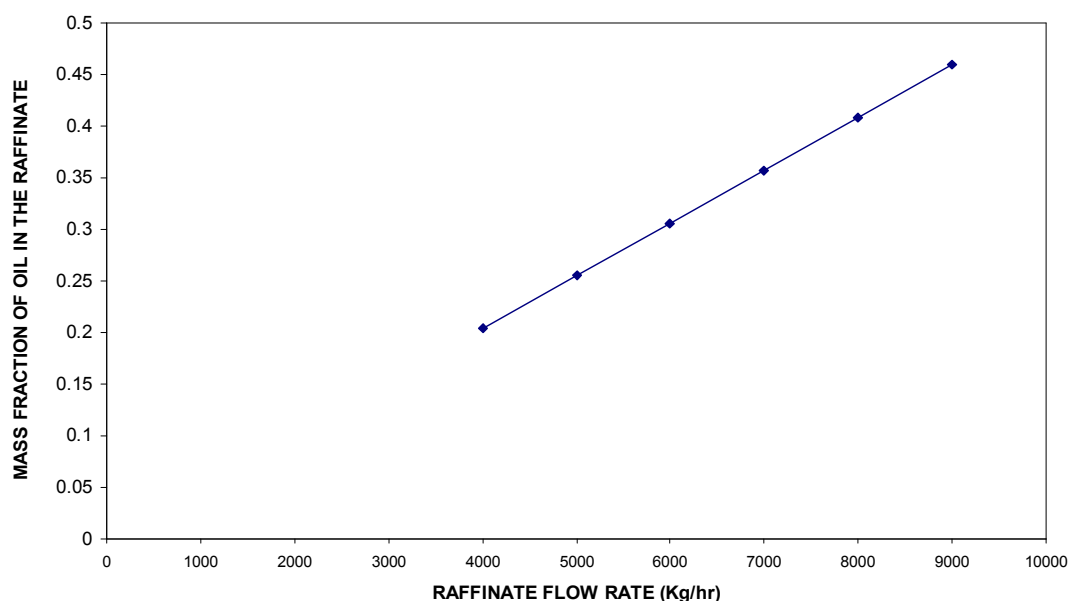


Figure 6. Effect of Raffinate (cake) Flow Rate on the Oil in the Raffinate.

4.3.2. Mass Flow Rate of the Solvent (Miscella)

The effects of extraction solvent mass flow rate on the amount of oil extracted and the amount of oil in the cake is also evaluated. Thus, an increase in the mass flow rate of the raffinate reduces the contact time between the solvent and the

cake which leads to poor extraction of the oil from the cake. The maximum amount of oil is extracted at the minimum flow rate of about 300Kg/hr, and a sharp decrease or decline in the amount of oil being extracted as the flow rate increases as shown in Figure 6.

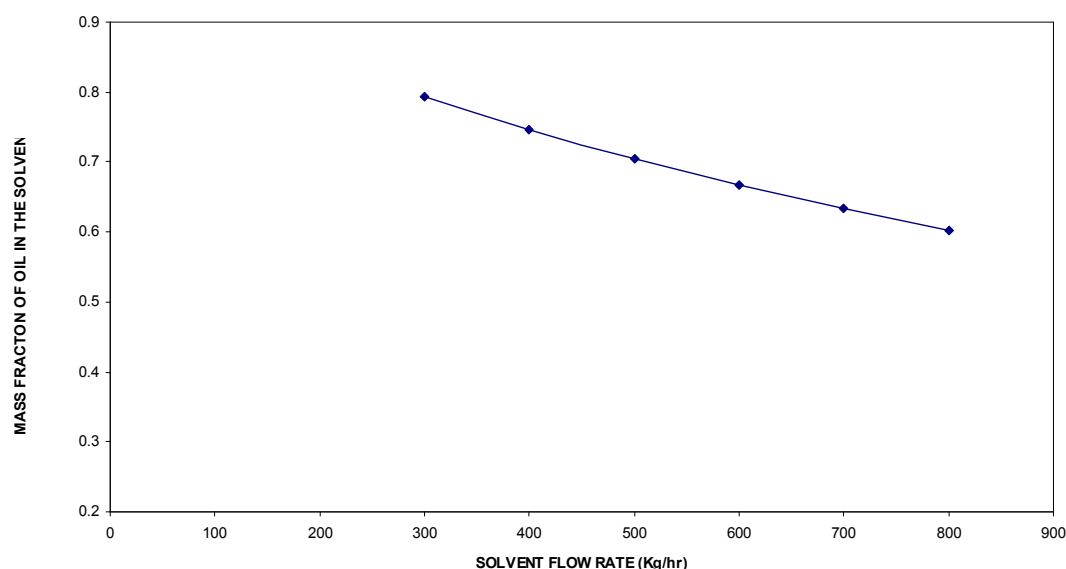


Figure 7. Effect of Solvent on the Amount of Oil Extracted.

5. Conclusion

The developed models can be used to predict the amount of oil extracted and the outlet temperature of the raffinate and extract of an extractor plant on the basis of material and energy balance equations. The models predicted these variables with high degree of accuracy, and the sensitivity analysis performed on the model shows the behaviour of an extractor plant to changes in the process variables considered. It also set the

boundaries and optimum values of the process variables tested. Thus, the developed models were evaluated by using plant data and its results compared with industrial extraction plant data with percentage deviation or absolute error of 7.0 and 3.29 for mass fraction of oil in the raffinate and extract and 9.52 and 2.29 for exit temperature of raffinate and extract respectively. These deviations showed a close mapping between the developed models and industrial extractor data, thereby validating the models application for extraction simulation.

Furthermore, the effects of mass flow rates of raffinate and extraction solvent were studied with increase in mass flow rate of raffinate reduces contact time between extraction solvent and the cake thereby yielding poor extraction process (reduction in extraction efficiency) and maximum amount of oil is extracted at the minimum flow rate of 300Kg/hr. Hence, these models are useful in planning, forecasting and predicting production output from the extractor unit and its simulation studies can be used in preventing plant trouble shooting and maintain efficient extraction operational process.

Nomenclature

R_{n-1} =raffinate (cake) flowrate (kg/hr) from stage n-1.

X_{n-1} =mass fraction of oil in the raffinate phase stage n-1.

R_n =raffinate (cake) flowrate (kg/hr) from stage n.

X_n =fraction of oil in the raffinate phase from stage n.

E_n =extract (miscella) flowrate (kg/hr) from stage n where.

M_t =total mass of oil within the system (both in raffinate and extract phase).

H_n =mass (kg) of oil in the raffinate phase (cake) of stage n.

h_n =mass of oil in the extract phase (miscella) at stage n.

K is the distribution coefficient.

X_n is the mass fraction of oil in the raffinate (cake) phase.

Y_n is the mass fraction of oil in the extract (miscella) phase.

E_T is the total energy (Enthalpy) of oil within the system for raffinate and extract phase.

$H_n Y_n$ is the mass oil in the extract phase at Nth stage.

$h_n X_n$ is the mass of oil in the raffinate phase at Nth stage.

C_p is the specific heat capacity of oil.

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