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Simulation of Centrifugal System for Oil-Water Separation in Waste Cooking oil Filtration System

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Abstract: An investigation and analysis of a centrifugal system for the separation of used cooking oil and water were presented in this research. The aim is to optimize the separation efficiency and enhance the recovery of oil from the mixture. The study utilizes fluid simulation techniques to model the behaviours of the fluid flow within the system and analyses its performance under different operating conditions. Parameters such as the velocity of the centrifugal system, flow rates of the inlet and outlet fluids, and the geometry of the system are considered. The obtained results were presented and compared with existing literature, highlighting the effectiveness of the centrifugal system in achieving oil-water separation. Additionally, velocity contour plots are generated to visualize the flow patterns and provide insights into the fluid dynamics. The findings contribute to a better understanding of the separation process and offer potential avenues for further optimization. The outcomes of this project have implications for the efficient management and recycling of used cooking oil, which is a significant environmental concern. The project provides valuable insights into the design and operation of centrifugal systems for oil-water separation and offers recommendations for future research and improvements.

Keywords: CFD, centrifugal system, oil separation, waste cooking oil.

1. Introduction

In a globalizing world, cooking oil is a commonly used item in many types of food preparation. The oil frying method is most common due to the contribution of good taste, attractive colour, and better food presentation. As this method is becoming more popular, the produced waste from cooking oil has increased. As a report states, waste cooking oil is broadly generated across the globe daily [1,2]. The European Union (EU) approximately produce 700,000-1,000,000 tons of waste cooking oil (WCO) yearly generally of the oil from snack food and French fries. An estimation of 40,000 tons per year of WCO is produced in countries such as China, Malaysia, Indonesia, Thailand, Hong Kong, India, etc. [3]. WCO refers to the fats and oils that are or have been used for cooking or frying in commercial or industrial food processing activity includes restaurants [4].

WCO is the continual use of plant-based lipids, such as sunflower, corn, margarine, coconut, palm, olive, soybean, oil, and canola, as well as animal-based lipids such as butter and ghee. WCO formed of triglycerides, mono-glycerides, diglycerides, and free fatty acids in varying amounts (5–20% by weight) which are produced during the frying process [5-7]. Fatty acids which are saturated and unsaturated are the principal components of triglycerides which may be utilized as initiation material to produce value-added products in a variety of industries. WCOs are more common in industrial applications which are related to many energy productions, by direct burning [8,9] or as the fusion of the biofuels [10,11]. Although its restriction, like its high free fatty acid (FFA) and water content, WCO could be regarded as the most propitious bio-oil feedstock [12,13].

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WCO jettison causes major concern throughout the world this constantly growing problem affects the everyday life of millions of people [14,15]. WCO can be gathered from many sources' food processing businesses, restaurants, and private houses by utilising a designated "recycle container," but public awareness is required [13,16]. In 2018 the WCO market was around $6041.2 million and is expected to grow to $8886.7 million by 2026, with a 5.0% compound annual growth rate (CAGR) between 2019 and 2026 [17].

Whenever cooking oil is used in a cooking procedure such as frying, sauté, roasting, etc., the existing water from the food product will emulsify with the cooking oil. Once the process occurs then the cooking oil will be classified as used cooking oil or waste cooking oil. Although there is various method of cooking oil filtration, the report is regarding the separation of waste cooking oil and the water content in the oil by using a mechanical device. The commercialization value of the device is very low in the user countries. The existence of the product is a low or limited quantity, in today's market where some locations only have the facility.

Due to these issues, this research will analyse the fluid flow behaviour of the fluid flowing through a convectional centrifugal setup, hence evaluate and compare the fluid flow results with pre-existing results of convectional centrifugal setup. To achieve the aims of this research, simulation work on a centrifugal system performs in oil filtration system to separate water from the used cooking oil and the amount (percentage) of the water being separated from the used oil will be perform. The behavior of the water and oil separator in the ability of separating water from the WCO will be determine in term of rate and percentage of oil and water separated in outlet.

2. Treatment of Waste Cooking Oils

WCOs are composed of a long chain of fatty acids primarily linoleic, linolenic, and oleic with the form of tri, di, and mono-glycerides and a variable percentage of free fatty acids (FFA); stand for a platform for raw materials in many industries [18]. During the frying process the chemical composition of the oil changes, which can be associated with food and tool contamination and decomposition, regardless of the relative number of impurities that are produced during the process is not raised. The chemical composition of WCOs can be qualitatively appraised through Nuclear Magnetic Resonance (NMR) analysis. Typically, the treatment of collected WCOs involves a first gross filtration aimed to remove solid materials dispersed in the oil. Then the raw material is directly introduced into the production without a specific need for decontamination/transformation steps. referring to specific applications, the WCO-raw material will be subject to different types of transformations [19].

The chemical composition of WCOs will be utilized to produce esters in basic media with the presence of alcohol (esterification). Following this route, the common esters that are produced in the process are Fatty Acid Methyl Esters (FAMEs), derived by the reactions with methanol, and Fatty Acid Ethyl Esters (FAEEs), which are obtained through esterification with ethanol. Usually, the FAMEs and FAEEs are used in the production of biodiesel [20]. FAEEs show some advantages concerning FAME as enhanced fuel properties, in terms of stability towards oxidation and superior lubricant power [21]. The assessment of acidity is very important in the fuel application case.

Glycerol is a makeshift alcohol to methanol and ethanol for the esterification process of WCOs. This process is known as glycerolysis instead, furthermore, as regards WCOs, formally regenerates, in part, the original composition of the oil. By transforming the FFAs contained in the waste, the glycerolysis process can be capitalized for the increased value of starting materials WCOs into added value-chemicals. Mono- and di-glycerides are used as surfactants [22] or as emulsifiers in the food, cosmetic, and pharmaceutical industries [23] while triglycerides are employed as additives in bio-diesel production [24,25]. The low miscibility of glycerol and waste oil affects the glycerolysis process. This is the challenge that has been faced for decades; optimized protocols, which usually employ high-temperature conditions, have been proposed. In recent times, milder WCO glycerolysis has been reported by Supradan et. al. [26], by using hexane as an etymology for mass transfer problems developed due to the low solubility of glycerol. Alternatively, Mazubert [27] proposed to perform the glycerolysis of FFA in a reactor system.

FA results are higher than 2.5%–3%, so the raw material is not suitable for Biodiesel, thus, in the previous steps the FA amount needs to be reduced. The limitation constitutes the pointers for the waste collectors, as that determines the price on selling when the WCO are delivered to respected facilities [28]. For companies which are involved in the dispensing and dispatching of the WCO, in huge or bulk amounts, the cost can be elevated. Compared to a small company, they can blend the FAs with different acidities to the level of requirement of the producer.

2.1 Impurities separation

There are several separation methods used to remove impurities and undesired products from waste cooking oil. The most physical routes for achieving waste cooking oil regeneration are separation based on solubility, separation through filtration with specific material and separation based on the boiling point (distillation).

For the separation based on solubility, water is the solvent option concerning the separation process based on solubility. As oil is unmixable with water, the chemicals contained in WCO can be easily eliminated by washing the coarse material. Utilizing a metallic tank with a mechanical stirrer fitted the procedure can be extended to an industrial environment. This structure has been known for years as degumming (for purifications of vegetable oil). The main purpose of this is to remove the phospholipids and waxes

[29]. Altering the pH of the water, to work at a specific temperature with a fixed stir time, the density may increase, the flash point, and the colour of the resulting bio-lubricant also reported changes to the degumming procedures, a small change can be seen in the density value, while the flash point is more sensitive to the process parameters [30].

Different with separation through filtration with specific material, the core of particle sequestration and separation is the recycling process, and its efficiency depends on the particulate that can be conserved, the volume of the filtrate that can be circulated through the filter, and the physicochemical properties of the filtered oil during the process. Rejuvenation of the physical and chemical waste frying oils can be commonly divided into three prominent technological advances: membrane treatment, conventional, and active filtration. Both mentioned approaches feats different solid materials, which characterized performances, cost, and sustainability of the whole recycling process.

The membrane technology application in vegetable oil processing has gained more notice due to its benefits, including low energy consumption (approximately 50% concerning conventional filtration), along with keeping the nutrient components [31]. Membranes can be classified as semipermeable barriers, which allow the passage of components (vegetable oil) and keep others (i.e., the undesired products produced after frying at a high temperature). The driven procedure by the pressure application and size of byproducts is membrane filtration. Two main classes of materials are used for producing commercial membranes are polymers consisting of cellulose acetate, polyamide, polysulfide, and polyvinylidene difluoride (PVDF).

Another separation method is separation based on the boiling point (distillation). The general procedure used on the raw material can be summarized as follows; the crude oil is heated under a vacuum after being treated to a gross filtration aimed to remove solid contaminants. The crude oil is isolated from the volatile fraction through reduced pressure distillation, producing a regenerated oleic product. After deodorization, recycled vegetable oil can be used to make soap, high-quality lubricants, low-quality lubricants, fuel, and raw materials for other industries, and low-quality lubricants [29].

The design approach of the machine as well as the quality of the raw WCO has such an influence on the recycled oil's quality. In fact, these machines can be used to create low-quality lubricants from trash, which can then be used, sold, or refined after being further processed. This technique can also be used by the end-user themselves to regenerate used lubricants that are used in close circuits. For instance, the market share for bio-lubricants is expanding quickly and had a Compound Annual Growth Rate (CAGR) of 5% in prior years, with the US and Europe serving as the key customers.

Recycled cooking oils can be turned into solvents or chainsaw lubricants by distilling, filtering, or combining the processes. In the first instance, more refinement may be required based on the desired quality, especially to increase the oxidation stability and pour point, for example, by esterification and/or by adding antioxidants [32]. In the second instance, recycled vegetable oil can be converted into a variety of derivatives, including glycerol, alkyds, poly (ester amides), poly (ether amide), polyurethanes, and epoxies. When combined with natural pigments, these materials can be used to create biodegradable coatings and paints [33].

3. Methodology and Numerical Procedure

The simulation in this study was conducted using various parameters to model and analyze the behavior of the fluid flow. These parameters play a crucial role in accurately representing the real-world fluid dynamics and understanding the system's performance. The chosen parameters include the velocity of the centrifugal system, the flow rates of the used cooking oil and water inlets, and the outlets' flow rates. These parameters were selected to simulate realistic flow conditions and enable a comprehensive analysis of the separation process. By considering these parameters, the study aims to provide valuable insights into the fluid behavior and optimize the separation efficiency of the centrifugal system.

A centrifugal system comes in various shapes and sizes to accommodate different use cases on wide range of applications. In this study, several specifications of centrifugal systems were searched to fulfill the objectives only one of the systems fitted to the objectives. From this we can take a different approach using the same shape but different dimension or size of components to further research. Table 1 shows the parameters chosen based on previous study by Nikita et.al [34].

Table 1 – Parameters for simulation work

Water concentration at inlet	Boundaries	Flowrate [m^3/h]	Water flowrate [m^3/h (%)]	Oil flowrate [m^3/h (%)]
12 %	Oil inlet	38	-	-
	Water inlet	5.2	-	-
	Cleared oil	2.2	0 (0)	2.28 (6)
	Draining	8.672	0.312 (6)	8.36 (22)
	Recirculation	32.4	4.888 (94)	27.36 (72
5.7%	Oil inlet	40.8	-	-
	Water inlet	2.4	-	-
	Cleared oil	2.2	0 (0)	2.2 (5.4)
	Draining	8.6	0.132 (5.5)	8.486 (20.8)
	Recirculation	32.4	2.268 (94.5)	30.11 (73.8)
2.2%	Oil inlet	42.25	-	-
	Water inlet	0.95	-	-
	Cleared oil	2.2	0 (0)	2.323 (5.5)
	Draining	8.6	0.019 (2)	8.45 (20)
	Recirculation	32.4	0.931 (98)	31.47 (74.5)

3.1 Simulation model

In this study, the scope is focused on simulating and comparing the fluid flow behaviour between three ranges of velocity. For that, the 3D model of the system was designed in SolidWorks. All 3 stages setup will happen within the system, where will surround by the inlet wall, which also houses the axial fan parallel to the inlet of the system. This will keep the fluid flowing within the system. A rough sketch for the system is shown below in figure 1 while the dimension of the model summarised as in Table 2.

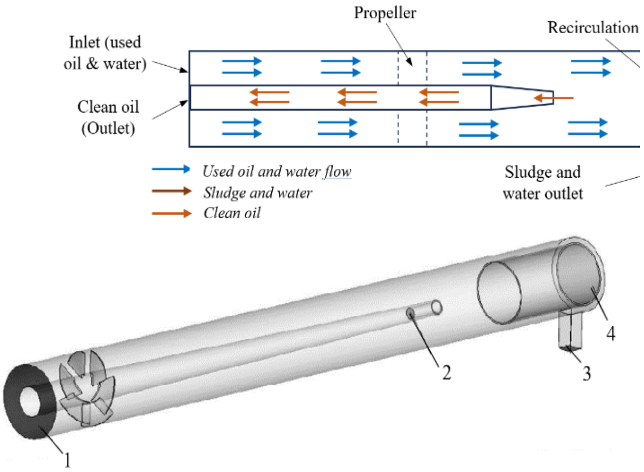

Fig. 1 – Oil separation system and 3D simulation model (1) Input stream, (2) output of clean product, (3) water and sludge outlet, (4) output stream for recirculation

Table 2 – Parameters for simulation work

Parameters	Dimensions
Length	1500 mm
Blade diameter	7.06 mm
Hub diameter	148 mm
Length of blade	94.02 mm
Thickness of model's main wall	20 mm
Flow inlet diameter	600 mm
Flow outlet diameter	41 mm
Thickness of outlet wall	2 mm
Length of outlet	800 mm
Length of water outlet	180 mm
Water outlet diagonal area	63.64 mm²

Figure 2 shows a block-structured hexahedral mesh finer to the walls for correct modelling processes proceeding in the boundary layer. Calculation of the full model in the two-phase statement requires considerable resources of computer time. Hence, in this case more efficient use the model with periodic boundary conditions.

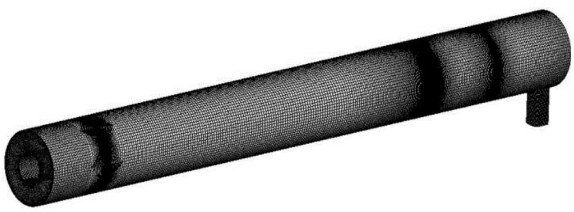

Fig. 2 – Meshing of the simulation model.

Setting the oil-water emulsion with a certain concentration ratio was not possible, so the concentration of water and oil are given zonally. All the water inlet is defined at a central portion thus modelled the most difficult option in terms of separation. Figure 3 shows the section choose for the periodic boundary conditions and Boundary conditions with oil fraction at the inlet set in the axial region.

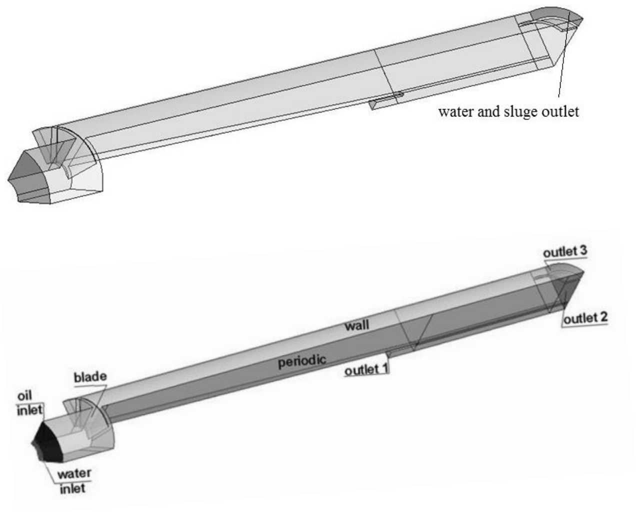

Fig. 3 – Geometrical model with periodic boundaries

3.2 Numerical setup and boundary conditions

A total of 3setups were used in this study to observe the liquid flow properties between these different setups. The parameters of the setups are shown below in Table 3.

Table 3 – Setup data for each numerical method analysis

Setup	Velocity (m/s)	Velocity Inlet (m/s) WCO	Water	RPM	Pressure (Pa)
Setup 1	2.5	2.512	2.509	500	
Setup 1	5	5.106	5.019	1000	101325
Setup 3	10	10.057	10.021	1500	

Three different velocities used in the setup; the initial velocity is 2.5 m/s referred from Nikita, K., et al. [34], which was the initial, the remaining setup was added which is setup 2 (5 m/s) and setup 3 (10 m/s). Since the sizes of the inlets are different the magnitude for velocity will also be different during the input for calculation in ANSYS. For the inlets the *x* vector will be the height of inlets, meanwhile the *y* vector will be the width of the inlets. For the height, width of used oil inlet will be 215 mm; 120.21 mm, and height, width of the water inlet will be 10 mm; 106.1 mm. The value of *z* which is distance 1500 mm as the length for all setups. The time taken can be found using the formula as well, time taken varies according to velocity; 0.6 s, 0.3 s, 0.15 s.

Conditions for solving the problem and results are as in Table 3. Due to low velocities (except interscapular channel guide vanes - up to 10 m/s) and large values of the viscosity the problem was solved in the laminar formulation.

Table 3 – Parameters for simulation work

Parameters	Values
Inlet	2 m/s
Outflow setting as the ratio of the total flow rate:	
- Outlet 1	5 %
- Outlet 2	75 %
- Outlet 3	20 %
Wall	No-slip condition
Solver	Segregated
Solver scheme	PRESTO
Courant number	0.25

4. Results and Discussion

The results from the simulation work provide valuable insights into tracking target flow variables and evaluating the convergence of the solution. From the obtained results, it shows that the centrifugal system achieved successful separation of the fluid flow when the velocity was set to 2.5 m/s. The system was able to separate 0.0110 m³/s of the mixture into 3 outlets. Outlet 2 had a value of -0.1485 m³/s, indicating that it predominantly recirculates the fluid flow. On the other hand, outlet 3 had a -0.0283 m³/s, indicating that it predominantly removed the fluid flow. Figure 4 shows that the results confirm an effectiveness of the centrifugal system in achieving separation.

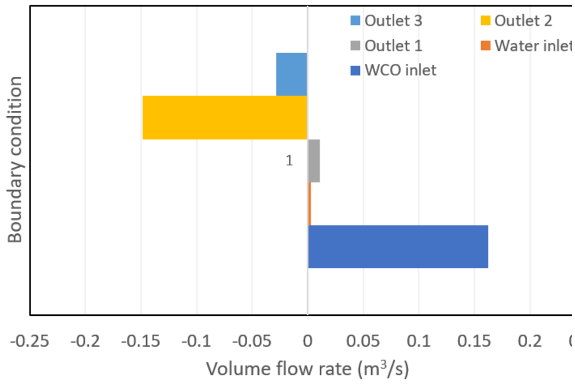

Fig. 4 – Centrifugal system for 2.5 m/s setting

Similar trend obtained for setup 2 and setup 3 which are the velocity were 5 m/s and 10 m/s, shown in figures 5 and respectively. The system was able to separate 0.0215 m³/s of the fluid flow into two outlets for setup 2. Outlet 2 had a negative value of -0.3010 m³/s, indicating a predominance of fluid flow, while Outlet 3 had a negative value of -0.0574 m³/s, indicating a predominance of fluid flow. This confirms the direction of fluid flow in all openings of the system. For the setup 3, the system was able to separate 0.0442 m³/s of the mixture into two outlets. Outlet 2 had a negative value of -0.5945 m³/s, indicating a predominance of the liquid flow, while outlet 3 had a negative value of -0.1133 m³/s, indicating a predominance of the liquid flow. This confirms the direction of the fluid flow in all openings of the system.

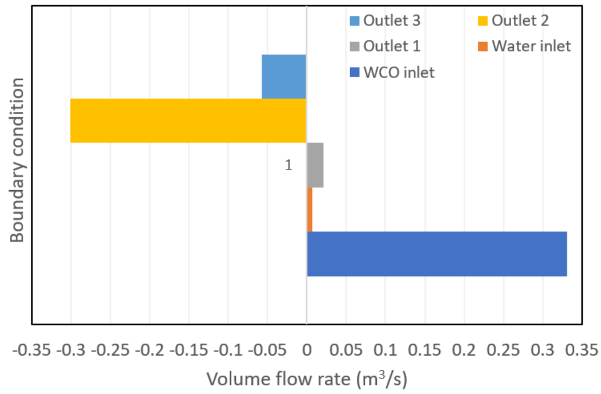

Fig. 5 – Centrifugal system for 5 m/s setting

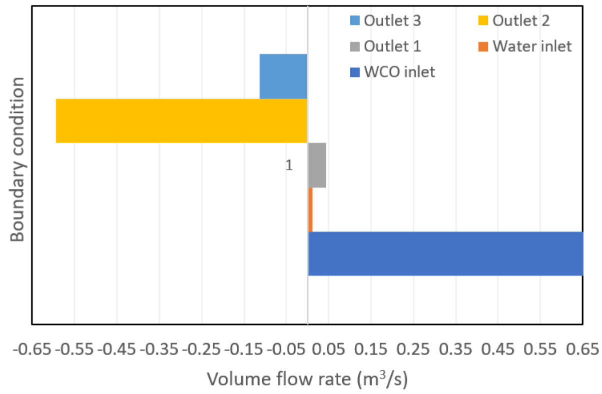

Fig. 6 – Centrifugal system for 10 m/s setting

The negative values for outlet 2 and outlet 3 indicate the direction of the fluid flow in the system. The negative sign signifies that the flow is in the opposite direction compared to the chosen reference direction. In this case, the negative values indicate that the flow in outlet 2 is directed towards removing water from the mixture, while the flow in outlet 3 is directed towards removing oil from the mixture. These findings highlight the capability of the centrifugal system to efficiently separate oil and water mixtures, which has practical implications in industries such as wastewater treatment and oil processing.

5. Conclusion

The comparison of the centrifugal system performance at different velocities (2.5 m/s, 5 m/s, and 10 m/s) reveals some notable differences. One crucial aspect is the variation in initial velocities, which determines the speed at which the fluid enters the system. When the initial velocity is lower than 2.5 m/s, the fluid may not be able to flow through the system efficiently, resulting in longer residence time within the inlet. Another significant factor is the speed of the rotating fan, which has three different settings: 500, 1000, and 1500 RPM. The fan's rotation speed plays a crucial role in generating the required swirl flow within the system, which is essential for the study.

The axial fan's purpose is to induce the swirl movement after the MRF zone, and different fan speeds can influence the size and speed of the swirl. Lower fan speeds tend to produce smaller swirls, which can affect the flow distribution and values obtained in the outlets. These differences in initial velocity and fan speed demonstrate the influence of operational parameters on the performance of the centrifugal system. Adjusting these parameters allows for control over the fluid flow behavior and separation efficiency within the system. It is important to consider these factors when designing and optimizing the centrifugal system for specific applications, as they can significantly impact the separation performance and desired outcomes.

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