Numerical investigation of coalescing plate system to understand the separation of water and oil in water treatment plant of petroleum industry

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ABSTRACT

The most widely utilized process of produced water treatment is considered to be use of coalescing or corrugated plate systems in the oil industry because these systems have promising results in the acceleration of the separation process. Even use of corrugated plate systems seem to be effective in separation processes, the geometrical parameters of the plate system could greatly influence the performance of separation process. In this study, a two-dimensional computational fluid dynamics model for coalescing plates was developed to investigate Reynolds number and plate hole shape on separation efficiency. Spacing between plates was set to 12 mm while fluid mixture's Reynolds number varied between 5 and 45 for the computational model. Hole profile and dimensions were determined to be cylindrical, rectangular and ellipse shapes as 10, 15 and 20 mm based on hydraulic diameter definition, respectively. Furthermore, when hole profiles of coalescing plates were chosen to be ellipse and rectangular shapes, separation efficiency nearly stayed constant regardless of hole dimension. The study also reported that change of oil fraction from 5% to 15% caused approximately 30% increase in the separation efficiency. The investigation also revealed Reynolds number of the mixture was inversely proportional to the separation efficiency. It was also found that the highest separation efficiency was obtained for a cylindrical shape with a hole diameter of 15 mm when distance between plates was 12 mm and Reynolds number was 18.

Nomenclature

| symbol | Description | unit |
|--------|-------------|------|
| $\mu$  | Viscosity of the fluid mixture | |
| $\rho$ | The density of fluid | kg/m$^3$ |
| $l$    | Characteristic length | mm |
| $v$    | Velocity of fluid mixture | |
| $\alpha$ | Oil volume fraction | |
| $\rho_1$ | The density of water | kg/m$^3$ |
| $\rho_2$ | The density of oil | |
| $v$    | Velocity of phase | m/sec |
| $M$    | Mass flow from each phase | kg/sec |
| $\nabla$ | Nabla or delta | |
| $\vec{v}$ | The velocity in the x and direction | m/sec |
| $\alpha_q$ | Volume of fraction of phase | |
| $S$    | Entropy | (kJ/kg.sec) |
| $h$    | Distance between plates | mm |
| $q$    | Second phase | |
| $m_{pq}$ | Mass transfer between phase $p$ and $q$ | kg/sec |
| $m_{qp}$ | Mass transfer between phase $q$ and $p$ | kg/sec |
| $F$    | Force | n |
| $\rho$ | Pressure drop | n/m$^2$ |

1. Introduction

The extraction way of crude oil typically determines the compound of the fluid mixture usually containing either gaseous hydrocarbon or liquid, suspended or dissolved solids, settling-like sand or slt, inserted fluids and additives (Veil, Puder, Elcock, & Redweik, 2004). Because of the high level of the toxicity and solubility in the remaining water, it carries a major environmental risk for humans (Zhaohui, Ashok, & Wilfred, 2003). There were major concerns about hydrocarbons because they have been considered to give rise to cancer and other serious diseases, in accordance with the USA environmental protection agency (Agency U.S.E.P., 1998). Therefore, decreasing exposure to these materials has been a fundamental issue for preserving marine and human life (Reusser & Field, 2002). As a result, governments have been setting regulations on elimination techniques of water from petroleum product mixtures. Currently, there are several techniques for removing oil in produced water. One of them is gravity separation which has been commonly employed due to its simplicity. The gravity techniques have been commonly used in a variety of applications in oil manufacturing for the separation of produced water because the gravity system is economically beneficial and entangles no moving parts. Therefore, the gravity technique has been accepted to be the most

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utilized separation method in the petroleum industry (Gu, 2001; Kenawy, Kandil, Fouad, & Aboarab, 1997; Ruiz & Padilla, 1996). Simple techniques are insufficient and more complex techniques are either required an intensive maintenance.

New efficient devices for the separation of the globules of emulsified oil produced from water by wavy coalesce plate were studied as first-class gasoline and oil separator prospects (Ostrovskii, 2003). In the study, the distances between plates were varied between 6 mm to more than 20 mm. The angles of 45 or 60 degrees were reported to be separating oil globules of 60–150 microns in coalescing inclined plates. Holes included in that design worked as assistance for the plate and insuring precise adjustment. The diameters of these holes differed from 10 to 15 mm (American Petroleum Institute API, 1990; Smith, 1993). Oily water streamed along the channels’ interval plates by a wavy path pursuing the gap shape and finally, turning upwards and downwards. Oil globules that have lower density than water move upwards and touch the bottom section of coalescing plates; therefore, they are retained owing to the adhesion force. When a large quantity of oil globules is arrested, it coalesces into big globules and alternately, shape a film. By the influence of the kinetic head of the fluid, the film passes to the top section of the plate and moves to the top of the channel and then gathers on the surface of the water. Holes for oil are adjusted undeviatingly over the surface of the plates by vertical lines. These holes supply access for the coalesced globules to the fluid surface in the system. This design appoints conditions for the efficient arrest for the oil droplets and their fast transmission to the surface (Ivanenko, Yablokova, & Petrov, 2010; USEA, 2011).

Use of algorithm in mathematical method was employed for calculating the separation efficiency by Ivanenko et al. (2010). The study compared the effectiveness of flow vision software and mathematical method. It was found that the flow vision software was complicated for solving three-dimensional (3D) equations for liquid dynamics. Therefore, the flow vision software was applied for simulating the separation process of emulsified oil from water in coalescer devices. The result showed that laboratory data from the pilot test of the coalescer plate separators have good agreement between the results of the flow vision software and experiments. Almarouf, Nasser, Al-Marri, Khraisheh, and Segheer (2015) designed a new and effective oil in water system equipped with a series of inclined multiple arcs. Corrugated plates were advanced and enhanced for subtracting stabilized oil mixtures from generated water. A series of exams were carried out to evaluate the properties of the arc coalescing plates and the influence of plate shape, generated water volumetric stream rate, influent oil density and handling temperature on the oil abstraction efficiency was utilized to have an advanced system. On the other hand, a number of researchers have utilized computational fluid dynamics (CFD) technique to examine oil water separation. This method has also been employed as a basis of oil water separation experiments because defining the effects of various geometries and operation processes on the efficiency of separation by carrying out experimentation can be complex and costly (Andreessen, Arntzen, & Sjøblom, 2000; Wang & James, 1998; Zhao, Hua, Wang, Ma, & Yan, 2005). CFD modeling has proven to be more applicable and advantageous compared to experiments (Cooper & Coronella, 2005; Zhong, Xiong, Yuan, & Zhang, 2006). Once the physical and chemical properties of the fluid are applied in modeling with CFD, the program solves the governing equations to provide output parameters for the fluid dynamics and associated physical phenomena. Thus, CFD modeling can be seen as a valuable computational-based design and analysis procedure (Nowakowski, Cullivan, Williams, & Dyakowski, 2004).

Zhi-an, Jie, Yu-ting, and Dan (2011) provided numerical simulation for oil/gas separator with different coalescing components using gravity. Their model included variety of plate shapes such as snake-shaped curve plates and employed k-ε multiphase mixture model. They reported that use of horizontal plates had worst coalescing effect. In another study, Oshinowo, Elsaadawy, and Vilagines (2014) utilized CFD model for three-phase separators to determine oil water separation efficiency. They emphasized the modeling of evolving droplet size during separation to be critical criteria for a separator model. In another study, Laleh, Svrcek, and Monnery (2012) investigated multiphase separators and reported that downstream equipments like compressors play an important role in oil and gas production plants for primary separation. They provided review study to highlight the importance of CFD simulations in optimization of separator designs and provide solutions for already existing designs. Yayla, Sabah, and Olcay (2016) performed CFD modeling on coalescing plate system to identify optimum distance between plates and they reported that 12 mm distance between plates with 0.02 m/s inlet velocity resulted in highest separation efficiency.

Water treatment plant required the separation of water from oil and the coalescing plates are widely utilized in separating water and oil mixture. Therefore, in this study, coalescing plate system was reinvestigated utilizing CFD model similar to Yayla et al. (2016) to determine best hole shape and inlet velocity from the CFD simulations. The study had constant distance between plates and varied hole shapes where oil was passing through (i.e. leaving
oil and water mixture). Inlet velocity was also varied to understand the effect of Reynolds number on separation efficiency.

2. Material and methods

Water treatment plant systems generally consist of six sections: inlet pipe used as entrance for penetrating oil/water to the system, storage tank to provide help to sediment particles and solid materials, coalescing plates to achieve separation of oil from water, oil skimmers to transfer the accumulated oil above the coalescing plate. Oil dam also acts as boundary line between separated oil and water and water outlet pipe to transmit clean water after separation outside the system. This entire system shown in Figure 1 is designed to separate oil from water with the help of the buoyancy of the oil droplets.

When types of separators are considered, there are mainly four types of separators used in practice. These are namely American Petroleum Institution (API) apparatuses, coalescing plate separators, coalescing tube separators, packing-type separators burns and Mohr. However, the most important separators are accepted to be API and coalescing (Mohr, 1995). Therefore, these separators were studied thoroughly in the present work. Figure 2 illustrates the working principle of a coalescing plate separator. Briefly, a mixture of oil and water enters into the separator and the oil stream moves into upward direction while the water stream travels with the main stream and exits from the right boundary.

The governing equations were solved by discretizing the computational model with a finite volume method. The solver scheme was first order accurate for space. While simple algorithm was employed for pressure-velocity coupling, convective terms were resolved by using quick scheme. Geometry of numerical model was generated using CAD module of ANSYS Workbench as shown in Figure 3. The length and width of the domain were determined to be 537 mm and 55.7 mm after the domain independence tests. Fluid flow direction was defined along the x direction. The shape of a plate has a length of 128 mm and height of 30 mm. Furthermore, plates were horizontally apart from each other with a hole diameter ($D_h$). In this study, circular, rectangular and ellipsoidal hole shapes were defined based on hydraulic diameter definition. The distance between plates ($h$) was set to 12 mm (Yayla et al., 2016). Left and right sides of the computational domain were defined as mass flow rate inlet and pressure outlet boundary conditions, respectively while plates, top and bottom sides of the domain were set to wall with no-slip boundary condition as illustrated in Figure 3. Mixture’s volume of fraction was set to three implying water to oil ratio was 3:1. Variations of average velocity, fluid velocity characteristics and separation efficiency were monitored and compared with the experimental findings of Ivanenko et al. (2010) for the mesh convergence. Furthermore, the change in these parameters was also evaluated by increasing the number of mesh in the computational domain. Mesh convergence tests revealed that the difference in these parameters stayed less than 5% for the comparisons of experimental work and computational domain with the largest number of elements. Therefore, a total of 39,000 quadrilateral elements were placed into the computational domain as shown in Figure 4. Sweep method was utilized for meshing to capture the free surface flow profile. In this technique, mesh size was refined along the direction normal to the fluid flow. This method also ensured placement of appropriate refinements near the plate thickness by maintaining first layer thickness. Minimum mesh size of 0.00014 m was used in the computational domain to capture gradients of velocity in the boundary layers of

![Figure 1. The water treatment plant system.](image_url1)

![Figure 2. A coalescing plate separator showing the inlet and outlet directions of water and oil streams.](image_url2)
plates. Mesh quality was also evaluated by considering
the mesh skewness. Specifically, skewness of 0.25 or less
was obtained for most of the elements while few elements
near the plate corners exhibited maximum skewness of
0.5. Furthermore, aspect ratio of the elements were also
monitored and average aspect ratio of 1.045 was obtained
for the computational domain implying that nearly all the
quadrilateral elements were squares. This range of aspect
ratio and skewness was also agreed by Bakker (2006).

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An important non-dimensional number in the charac-
terization of the flow regime, namely Reynolds number,
was defined based on the characteristic length of geom-
etry, average velocity and fluid properties. In this study,
Reynolds number (Re) was expressed as 
\[ Re = \frac{\rho m V h}{\mu m} \]
for two-phase flow because mixture of oil and water was
used in the flow domain. Here, mixture density (\( \rho_m \))
was obtained from 
\[ \rho_m = \alpha \rho_2 + (1 - \alpha) \rho_1 \]
while mixture viscosity (\( \mu_m \)) was calculated from 
\[ \mu_m = \alpha \mu_2 + (1 - \alpha) \mu_1 \]
(Ansys fluent theory 2009; Awad, 2012). In these
equations, \( \rho_1 \) and \( \rho_2 \) were densities of the water and oil,
respectively while \( \mu_1 \) and \( \mu_2 \) were the dynamic viscosi-
ties of the water and oil, respectively. \( V, h \) and \( \alpha \)
represent velocity of fluid mixture, distance between plates
and fluid fraction in the mixture. In this study, \( Re \) was cal-
culated by setting the mixture to be 75% water and 25%
oil for the fluid mixture. Reynolds number of the fluid
mixture varied from 12 to 95 in this study guarantying
that the fluid flow stayed laminar during fluid flow simu-
lations because the critical Reynolds number for this flow
was reported to be 500 (American Petroleum Institute,
1990; Mohr, 1993).

Governing equations for the fluid flow consist of vol-
ume of fraction and momentum equations. Steady state
form of the continuity equation for the volume fraction
of one or two phases is given in Equation 1. The following
expressed the volume of fraction equation (Ansys Fluent
Theory, 2009; Lakshmi, 2006).

\[
\nabla \cdot (\alpha_q \rho_q \vec{v}_q) = S_{\alpha q} + \sum_{p=1}^{n} \left( \dot{m}_{pq} - \dot{m}_{qp} \right) 
\]

Here, \( \alpha \) is volume of fraction, \( S_{\alpha q} \) is source term, \( p \) is main
phase, \( q \) is secondary phase, \( \vec{v} \) is velocity of each phase, \( \rho \)
is fluid density, \( \dot{m}_{pq} \) is mass flow rate of the main phase
while \( \dot{m}_{qp} \) is mass flow rate of the secondary phase. In the
present study, water was defined as a primary phase while
the oil was identified as a secondary phase.
Momentum equation given in Equation (2) was also solved for the computational domain and the velocity field was shared between the phases. This equation was expressed as reliant on the volume fractions of each phase throughout the characteristics of $\rho$ and $\mu$.

$$\nabla \cdot (\rho vv) = -\nabla p + \nabla \cdot [\mu(\nabla v + \nabla V_t)] + \rho g + F \tag{2}$$

Here, $p$ is pressure, $v$ is velocity of each phase, $\mu$ is viscosity of fluid, $\rho$ is fluid density, $g$ is acceleration of gravity, $F$ is body force and $V_t$ is the resultant velocity.

The separation performance of an oil-water separator system was determined based on the amount of water removed from the oil-water mixture (Arntzen, 2001; Chen, Wu, Lu, Huang, & Zhao, 2015; Nour, Mohd, Has-san, & Yunus, 2007). Specifically, oil removal efficiency can be expressed as $(W_I - W_O)/W_I$ and here $W_I$ and $W_O$ represent water inlet and outlet oil content, respectively.

### 3. Results and discussion

#### 3.1. Velocity field in the coalescing plate

Obtaining velocity field between coalescing plates played an important role in the understanding of the physics of fluid flow in the coalescing plate system in this study. Briefly, oil and water mixture entered into the coalescing plate system from mass inlet boundary and the mixture had to follow the fluid path directed by the coalescing plates as shown in Figure 5. The fluid mixture initially at 0.02 m/s accelerated when the mixture passed through coalescing plates. Once the mixture arrived at the end of curvature, the fluid mixture split into two ways. While fluid with high velocity preferred to move above the coalescing plates, fluid with low velocity had to travel through coalescing plates. Enlarged view of this separation is illustrated in Figure 6. Furthermore, the high velocity fluid caused rotational fluid zones underneath the wall as seen in Figure 6. Therefore, use of coalescing plates indicated that the separation process was accelerated. This means that the separation efficiency was high and end of curvature showed that small vortex flow appeared and fluid flow was rotating due to flow separation.

In addition to fluid mixture’s velocity magnitude, y-component of fluid mixture’s velocity is plotted in Figure 7. The higher y-velocity fluid outside the coalescing plates implies that one fluid moves upward while the other one travels downward due to the density difference. Therefore, mixture’s y-velocity component can be evaluated for the separation of bulk phase (Ivanenko et al., 2010; Mastouri, 2010).

#### 3.2. Volume of fraction of water

Determination of water’s volume of fraction is a measure of the performance of the coalescing plates system. Therefore, volume of fraction of water was calculated and shown in Figure 8 for the computational domain. It was noted that the left side of the domain mixture possessed nearly 70% water content while the right side of the domain had almost over 90% water at the lower part of the computational domain. This indicated that when fluid mixture moved from the left side of the domain

![Figure 5. Magnitude of fluid mixture velocity for $h = 12$ mm and $Re = 18$.](image)
Figure 6. Enlarged view of fluid mixture’s velocity Vector for $h = 12$ mm and $Re = 18$.

Figure 7. Mixture’s $y$-velocity component for $h = 12$ mm and $Re = 18$.

Figure 8. Water volume of fraction for $h = 12$ mm and $Re = 18$. 
toward to the right side, water and oil were separated from each other due to the differences in densities. As a result, water being the heavier one occupied zones close to the bottom wall while oil with lighter density stayed near the upper wall agreeing with Sampaioa, Faccinia, and Su (2008).

3.3. Separation efficiency study

In this study, separation efficiency was evaluated for the coalescing plates systems and Figure 9 shows the comparison of the current study’s separation efficiency with the experimental study’s results. It was noted that the numerical findings of separation efficiency had a good agreement with the separation efficiencies obtained with performed experiments (Ivanenko et al., 2010) for the various Reynolds numbers.

Once the validation of the computational model was performed, three different hole geometries (i.e. rectangular, cylindrical and ellipse shapes) with three different sizes (i.e. 10 mm, 15 mm and 20 mm) were placed on the coalescing plate systems. Variation of separation efficiency for different rectangular shape holes were plotted in Figure 10. It was realized that the dimension of rectangular shape hole had nearly no effect on the separation efficiency while increase in Reynolds number led to a decrease in separation efficiency of the fluid mixture. This indicated that higher separation efficiencies could be obtained at lower Reynolds numbers in the coalescing plate systems.

Coalescing plate systems with cylindrical and ellipse shape holes with different sizes were studied and the results of cylindrical and ellipse shape holes were shown in Figures 11 and 12, respectively. Specifically, Figure 11 indicates that separation efficiency of coalescing plate systems had a strong dependence on dimension of cylindrical shape holes. For example, the coalescing plate system with cylindrical shape hole of 15 mm exhibited nearly 30% higher separation efficiency compared to the coalescing plate system with cylindrical shape hole of 20 mm. While the dimension of cylindrical shape holes were crucial for separation efficiency, Figure 12 implies
that ellipse shape holes had almost negligible effect on separation efficiency.

In addition to holes’ shape and dimension, the effect of distance between the coalescing plates on separation efficiency was investigated and the findings are exhibited in Figure 3. It was realized that when the distance between the coalescing plates was increased, the separation efficiency of the coalescing plate systems sharply decreased. This implied that having 8 or 12 mm distance between coalescing plates could provide above 70% separation efficiency for all the studied models. Particularly, separation efficiency reached over 90% when Reynolds number was less than 30. This indicated that high separation efficiency performances could be achieved for low Reynolds number flows. This is probably due to the fact that when the flow has lower velocity, buoyancy effects become dominant compared to the inertial effects. Besides, dominant buoyancy forces can reveal the vertical motion of the fluid mixture due to the density difference of oil and water. This can accelerate the separation process in the coalescing plate systems.

Table 1. shows the results when space between plates was 12 mm. It can be seen that the decrease in separation efficiency when inlet velocity of the mixture was varied from 0.020 to 0.050 m/sec. It was also noted that increase in the inlet velocity of the mixture caused increase of quantity of water outlet oil content or oil outlet which could be the sign of inefficient separation process. The separation efficiency was declined from 99.25% to 24%.

4. Conclusion

In this study, a numerical investigation was performed to understand the two phase flow phenomenon in coalescing or corrugating plate separators. Especially, the focus of the study was on the separation of water from oil-water mixture. A two-dimensional CFD model provided velocity vectors and fluid’s volume of fraction in the computational domain to identify the separation process. Besides, separation efficiency of fluid mixture was calculated for a variety of distances between plates, Reynolds numbers and hole profiles and dimensions. The results revealed that 15 mm diameter cylindrical hole shape placed on coalescing plates provided highest separation efficiency while ellipse and rectangular shape hole profiles on coalescing plates regardless of their dimension did not make any significant change on separation efficiency. It was revealed that when the oil fraction was 5% the separation efficiency was 77%; however, when the oil fraction was 15% the separation efficiency was nearly 99%. This research reported the use of different hole shapes based on hydraulic diameter definition and cylindrical shape hole with Re = 18 yielded highest separation efficiency when distance between plates was 12 mm.

Limitation of this work was about utilization of two-dimensional CFD model. Although the flow in the plate system is considered to be laminar, separation of water from oil and water mixture requires flow separation behind the curve shape plates. Therefore, the future work would include three-dimensional study of coalescing plate systems so that fluid flow characteristics around holes can be better understood. $\alpha_q$

Disclosure statement

No potential conflict of interest was reported by the authors.

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