Separation dynamics of immiscible liquids

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Abstract

In this paper, the geometric design of a gravity-based separator is studied with a computational fluid dynamics method. ANSYS Fluent (18.2) is used to model the ratio of horizontal and vertical lengths with three dimensionless groups. A dimensional analysis method is used to develop a new correlation of separator geometric design. Corresponding plots were created and analyzed using nonlinear regression on the x–y Cartesian coordinate system. Also, manual iterations were performed to determine the coefficients in the general correlation relationship. The dimensional analysis results show that the Reynolds and Euler numbers have a direct correlation with separator design, which means increasing the Reynolds and Euler numbers require a separator with a larger length to height ratio to achieve the same separation efficiency. However, the Weber number has an inverse correlation with separator design, which means an increase in the Weber number requires a separator with a smaller length to height ratio. The new correlation developed in this paper can be used as a reference for separator geometry design to separate immiscible fluids with a wide range of fluid properties.

Keywords Multiphase · Separation · CFD · Dimensional analysis

List of symbols

H	Separator theoretical minimum height (m)
L1	Bottom location of the interface layer (m)
L2	Top location of the interface layer (m)
P	Operating pressure (kPa)
t	Residence time (s)
x	Separator theoretical minimum length (m)
y	The vertical location of L1 (m)

ρ	Density (kg/m ³)
μ	Dynamic viscosity (N s/m ²)

Subscripts

v	Vertical direction
w	Water
o	Oil
m	The mixture of oil and water
k	Phase k

Dimensionless groups

$t^* = \frac{v \cdot t}{y_t^2 \cdot \epsilon_w}$	Dimensionless time
$y^* = \frac{y_t \cdot \epsilon_w}{P_w}$	Dimensionless length
$Eu = \frac{y_t \cdot \epsilon_w}{P_w}$	Euler number
$Re = \frac{\rho_m \cdot v^2}{h \cdot v^2 \cdot \rho_m}$	Reynolds number
$We = \frac{h \cdot v^2 \cdot \rho_m}{\sigma_{o/w}}$	Weber number

Abbreviations

API	American petroleum institute
CFD	Computational fluid dynamics
PISO	Pressure implicit with splitting of operator
VOF	Volume of fluid
2-D	Two dimensional

Greek symbols

ϵ	Volume fraction
σ	Surface tension (N/m)
v	Velocity (m/s)

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1 Introduction

The application of oil/water separators as a liquid/liquid separator is essential to a variety of important industries, such as offshore platforms [1], crude oil dewatering, and wastewater treatment [2]. The physical orientation of a gravity-based separator plays an essential role in determining the performance of a separator by affecting the separation efficiency. Both experimental and numerical methods have been used to investigate this critical area, and they show that horizontal separators are more economical and provide higher separation efficiencies [3, 4]. In a gravity-based separator, separation relies on the difference in the specific gravities of the phases. The simplest form of a horizontal multiphase separator is shown in Fig. 1. The main component of a separator is called the segment section, which provides enough residence time for the less-dense phase to coalesce and separate from the denser phase.

The inner components structure of a gravity separator directly affects its performance by changing the residence time of the mixture [5, 6]. Keller [7] studied the effect of the inner component, the filter media system, on the separation process with an oil density between 11 to 70 API. The study found that the design of filters affects the size distribution pattern of oil droplets, thus affecting the separation process. Rowley and Davies [8] proposed a sedimentation-oriented model to better represent oil droplets between parallel plates, which enabled the smallest oil droplets to coalesce faster in a gravity separator. Lars Schlieper et al. [9] investigated the separation behavior of a horizontal gravity separator with three different inner plates. Their study mainly focused on the relationship between the inflow to the plates, plate material, and the distance between plates and the separation length. Based on the results, they proposed that a separator with inner components, such as plates, can be an appropriate addition to the separator design.

Fig. 1 Schematic of a typical horizontal gravity separator

Fitnawan et al. [10] investigated the inclined gravity downhole oil–water separator. Based on their study, this separator type has several advantages, including long-life potential due to the simplicity of its components and its robust structure. Fitnawan et al. examined the performance of the separator setting depth, setting inclination, tubing size, and tubing configuration. The simulation results showed that for a water volume fraction of 81% to 87%, the inclined separator was able to obtain an oil/water separation efficiency up to 82%.

Along with the need to analyze the geometric design of separators, there is also a gap in knowledge with regards to the modeling of separators. Many researchers have focused on droplet coalescence and breakup modeling development [11–13]. A previous study on the water droplet coalescence model was presented by Prince and Blanch [11]. Their coalescence model separated the coalescence process into three steps: (1) the droplet approaching process; (2) the droplet film drain process; (3) the new droplet form process. The results are widely adopted by other studies on coalescence modeling [14–17]. Testik [18] developed a droplet collision model based on collision kinetic energy and surface energy. All of these developed models are used to describe the droplet coalescence process. The research does not consider variations of reservoir conditions in the field. Even within one reservoir, the amount of oil volume fraction changes during a reservoir's lifetime. These variations exert a potential effect on oil/water separation efficiency, which in turn affects the performance of the separator. However, there are only a few published studies regarding the relationship between the geometric designs of a separator and the physical properties of fluids. Therefore, fundamental research is needed to fill this gap.

Based on the existing gaps in separator design for immiscible fluids, this paper numerically investigates the effect of several oil/water mixture conditions on separator design. A 2-D separator geometry is simulated with ANSYS Fluent (18.2) for numerical investigations. The simulation results are compared with experimental data to validate the accuracy of the numerical predictions. A parametric study of numerical predictions is employed to investigate several critical variables, such as inlet flow rate, temperature, and operating pressure's effect on separation dynamics and separator geometry design.

Additionally, a series of simulations are conducted to validate this new correlation by changing the values of the dimensionless groups. A new correlation is developed by using the simulation results for the design of the separator as a function of three dimensionless groups. The new correlation is evaluated by comparing the results from several simulations.

2 Methodology

2.1 Experimental method

A gravity-based horizontal separator with length, width, and height of 2.28 m, 0.3556 m, and 0.3556 m, respectively, are used to conduct the experimental testing. Figure 2 illustrates the apparatus for the experimental loop that is used in this study. It consists of two centrifugal pumps (McMaster-Carr), two flow meters (OMEGA FTB-956), a pressure sensor (OMEGA DPG409-O50DWU), a thermocouple (NI 9211), and a PVC inline pipe mixer (McMaster-Carr). White mineral oil with a density of 872 kg/m^3 and viscosity of 15 cSt is mixed with water to obtain the multiphase fluid for the experimental study. The two fluids are pumped from two separate lines and are joined at a tee-junction; they then pass through the main pipe (diameter of 1-inch) and flow into the separator where the primary separation process takes place. An inline pipe mixer with 12 blades is placed in the pipe to ensure adequate mixing for each experimental test. The mixer is located 2 inches in front of the separator. The

target parameter in this experiment is the separation efficiency, which is defined as the oil volume fractions (ε_o) in the water phase. The value of ε_o is determined by taking three samples per minute from bottom locations throughout the separator. Three sampling locations are shown in Fig. 3: P1, P2, and P3. The uncertainties are obtained directly from the sample measurements and all the sensors and flow meters used in this experiment. According to Kline and McClintock's [19] uncertainty analysis method, the multiple measurement uncertainty of this study was $\pm 2.75\%$.

2.2 CFD numerical modelling method

The transient incompressible two-phase Navier–Stokes equation is used to predict the immiscible liquid separation. By assuming that temperature is constant during the separation, the governing equations are

$$\nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

Fig. 2 Schematic of the experimental apparatus

Fig. 3 The 2-D simulation geometry of a gravity-based separator

$$\frac{\partial}{\partial t}(\rho \mathbf{V}) + (\rho \mathbf{V} \cdot \nabla) \mathbf{V} = -\nabla p + \mu \nabla^2 \mathbf{V} + \rho \mathbf{g} + \mathbf{F} \quad (2)$$

where ρ is the density, vector $\mathbf{V}$ is the velocity as a function of two-dimensional space and time, $\mathbf{g}$ is the gravitational force, and $\mathbf{F}$ is the external force. Equations (1) and (2) represent the continuity and momentum equation, respectively.

2.2.1 The volume of fluid method

The following assumptions are maintained to apply the multiphase flow model: (a) the droplets in the dispersed phase are equally dispersed in the continuous phase; (b) the interpenetration between oil and water is ignored, which means oil and water are immiscible with each other; (c) all phases are incompressible; (d) density and viscosity are both constant in the calculation domain; and (e) no backward flow in the oil and water outlet, which means the gauge pressure at the outlet is zero.

The VOF model, which is designed for two or more immiscible fluids, is utilized for modeling the motion of the continuous phase and the discrete phase motion [20–23]. In this paper, the water is maintained as a continuous phase. In the VOF model, a single set of momentum equations is shared by the phases, and the volume fraction of each phase in each computational cell is tracked throughout the domain. In each control volume, the volume fraction sum of all phases is one. The fields for all variables and properties are shared by the phases and represent volume-averaged values, as long as the volume fraction of each of the phases is known at each location. When the volume fraction of phase one is 1 at certain computational cells, it means only this phase exists in these cells, whereas, if volume fraction is 0, there is none of this phase in the cell. When the fraction is between 0 and 1 ($0 < \text{fraction} < 1$), it indicates that both phases exist in this domain. The volume fraction equations in this model are as follows.

The volume fraction continuity equation is

$$\frac{\partial \varepsilon_i}{\partial t} + \vec{u} \nabla \varepsilon_i = 0 \quad (3)$$

where

$$\sum_{i=0}^{\infty} \varepsilon_i = 1 \quad (4)$$

The momentum equation is

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot [\mu (\nabla \vec{u} + \nabla \vec{u}^T)] + \rho \vec{g} + F_s \quad (5)$$

$$F_s = 2\sigma \kappa \alpha_i \nabla \alpha_i \quad (6)$$

where σ is the surface tension coefficient, $\vec{u}$ is the velocity, μ is the dynamic viscosity, α_i is the volume fraction of phase i , and κ is surface curvature.

In this study, for the viscous model, a laminar model is selected since the separation process is in the laminar region. A total simulation time of 30 min is maintained for all cases.

2.2.2 Numerical schemes and boundary conditions

A standard initialization with a Pressure Implicit Splitting of Operator (PISO) scheme for pressure–velocity coupling is selected. The governing equations, the initial conditions, and the boundary conditions are solved in Fluent 16.2. The inlet boundary condition is set as the velocity inlet, and the pressure outlet is set as the atmosphere pressure (101.325 kPa). Wall boundaries are set on the surface of the separator, and the cell zone medium is a multiphase flow.

The absolute residuals for momentum equations for each direction (x , y) and the continuity equation are set as 1×10^{-5} . The time step value is set as 0.0001, with a maximum iteration for per time step of 50. The stability of the numerical computation is achieved by setting the under-relaxation factors of Pressure, Momentum, and Reynolds stresses as 0.3, 0.3, and 0.5, respectively. These values were defined explicitly in this numerical study to improve the convergence.

2.2.3 Grid independence

A 2-D two-phase separator model is used in this study. The length of the computational domain is 1.776 m, and the width is 0.3556 m. Baffles are not considered in this geometry because the main objective is to study the primary geometric design of a separator, the length, and height. The location of the inlet is 0.254 m below the top. The grid is generated with quadrilateral face elements. There are no prism layers defined along with the boundary layer since the separation process is occurring in the entire computational domain. Therefore, a grid independence solution is conducted to compare the numerical solution of oil volume fraction for five different sizes of the grid (Table 1).

The oil volume fraction and the changes in the oil volume fraction (predicted with different grid sizes) are presented in Table 1. A plot of the grid independence study is presented in Fig. 4. The comparison of oil volume fraction with grid size (Fig. 4a) shows that grid size (#2) with 393,540 elements and 196,000 nodes is in the optimal mesh for this simulation. In addition, simulation results, which are predicted by grid #2, is validated with an experimental study. Figure 4b shows a comparison of the time series of the oil volume fraction at point (P2) for this grid size (#2) with the experimental results. The experimental

Table 1 Grid independence study for separation efficiency

Grid	Quantity of Elements	Quantity of cells	Calculated oil volume fraction	Change in oil volume fraction (%)
# 1	1,089,744	543,589	0.9301	–
# 2	393,540	196,000	0.9287	0.15
# 3	154,963	77,000	0.8714	6.31
# 4	98,770	49,000	0.8458	9.06
# 5	25,586	12,600	0.8091	13.01

Fig. 4 Structural grid independence study: **a** the effect of grid number on simulation results, **b** Comparison between experimental data and model predictions for the Base Case

uncertainty for the oil volume fraction calculation is 9%, with the numerical approach over predicting in comparison with the experimental results. As illustrated in Fig. 4, a good agreement has been found between grid #2 and the experimental data. A time dependence study is also performed to obtain relatively high calculation accuracy.

2.3 Dimensional analysis method

In this paper, a dimensional analysis method was used to develop a generalized correlation between the geometric design of a separator and various influencing factors on a gravity-based horizontal separator. The dimensionless Π terms are selected for this analysis to determine a relationship between the separator geometry and operating conditions' effect on separation efficiency. The theoretical minimum length (x) of a separator that is needed to achieve full separation depends on the separator height (h), fluid velocity (v), multiphase fluid viscosity (μ_m), multiphase fluid density (ρ_m), the interfacial tension between two phases ($\sigma_{o/w}$), and operating pressure (P), which is demonstrated in the following equation,

$$x = f(h, v, \mu_m, \rho_m, \sigma_{o/w}, P) \quad (7)$$

Each variable is presented in Table 2 by fundamental dimensions of mass (M), length (L), and time (T). Based on the Buckingham Π Theorem [24], four dimensionless Π terms are determined, as presented in Table 3. The resulting relationship based on this analysis is as follows:

Table 2 Description of the various parameters in fundamental dimensions

Variable	Description	SI units	Dimensions
x	The separator theoretical minimum length	m	L
h	The separator theoretical minimum height	m	L
v	Fluid velocity	m/s	LT^{-1}
ρ_m	density of multiphase fluid	kg/m^3	ML^{-3}
μ_m	Dynamic viscosity of the multiphase fluid	$kg/m \cdot s$	$ML^{-1}T^{-1}$
$\sigma_{o/w}$	Surface tension between oil and water	N/m	MT^{-2}
P	Operating pressure	Pa	$ML^{-1}T^{-2}$

Table 3 Dimensionless Π terms

Π Terms	Dimensionless Group	Name
Π_1	$\frac{x}{h}$	Separator length-height ratio
Π_2	$\frac{h \cdot v \cdot \rho_m}{\mu}$	Reynolds number
Π_3	$\frac{\rho_m \cdot v^2}{P}$	Euler number
Π_4	$\frac{h \cdot v^2 \cdot \rho_m}{\sigma_{o/w}}$	Weber number

$$\Pi_1 = \emptyset(\Pi_2, \Pi_3, \Pi_4) \quad (8)$$

or

$$\frac{x}{h} = C \cdot \left(\frac{h \cdot v \cdot \rho_m}{\mu} \right)^{n_1} \cdot \left(\frac{P}{\rho_m \cdot v^2} \right)^{n_2} \cdot \left(\frac{h \cdot v^2 \cdot \rho_m}{\sigma_{o/w}} \right)^{n_3} \quad (9)$$

Here the mixture density and the mixture viscosity are defined as

$$\rho_m = \sum_{k=1}^n \alpha_k \rho_k \quad (10)$$

$$\mu_m = \sum_{k=1}^n \alpha_k \mu_k \quad (11)$$

where k and α represent the phase and volume fraction, respectively. Changing the volume fraction of each phase changes the density and viscosity in the mixture. According to Sydney's [25] study, the relation between temperature and surface tension is linear through a relatively small temperature range (20–65 °C). Therefore, this linear

relationship between surface tension and temperature is maintained in this study.

3 Results and discussions

3.1 Operating conditions effect

The systematic study of operating conditions, including inlet velocity, oil volume fraction, temperature, and pressure, are listed in Table 4. All the values in the Base Case are maintained in the experimental study. The minimum oil volume fraction of 0.2 and an inlet velocity of 13×10^{-3} m/s are selected according to the measurement range of the flow meter. A temperature of 20 °C is selected for the Base Case. The separation process operates in atmospheric pressure.

The location of the interface layer is used to track the separation process. As shown in Fig. 5, Location 1 (L_1) represents the bottom of the interfacial layer, which means there is only a water phase under Location 1. Location 2 (L_2) represents the top of the interfacial layer. Dimensionless time (t^*) and dimensionless distance (y^*) are used to analyze the effect of operating factors on the separation process,

$$t^* = \frac{v \cdot t}{y_t^2 \cdot \varepsilon_w} \quad (12)$$

where v is the kinematic viscosity of water, y_t is the theoretical thickness of the multiphase fluid, which represents the height of fluid in the separator (Fig. 5), t is the resident time, and ε_w is the water volume fraction. The dimensionless distance can be represented by

Table 4 Simulation cases for various operating conditions

Case	Inlet velocity (m/s)	Oil VOF ε_o	Temperature (°C)	Pressure (kPa)	Surface tension (N/m)
Base Case	0.0137	0.2	20	101.325	0.0356
Case 1	0.0274	0.2	20	101.325	0.0356
Case 2	0.0374	0.2	20	101.325	0.0356
Case 3	0.0137	0.5	20	101.325	0.0356
Case 4	0.0137	0.8	20	101.325	0.0356
Case 5	0.0137	0.2	32	101.325	0.0356
Case 6	0.0137	0.2	40	101.325	0.0356
Case 7	0.0137	0.2	50	101.325	0.0356
Case 8	0.0137	0.2	20	344.738	0.0356
Case 9	0.0137	0.2	20	698.476	0.0356
Case 10	0.0137	0.2	20	1034.214	0.0356
Case 11	0.0137	0.2	20	101.325	0.0365
Case 12	0.0137	0.2	20	101.325	0.0389

Bold for each case stands for the main changes in the investigation value

Fig. 5 Phase distribution in the separator

$$y^* = \frac{y_r}{y_t \cdot \epsilon_w} \quad (13)$$

where y_r is the thickness of the separated water phase (Fig. 5).

3.1.1 Effect of oil volume fraction (ϵ_o)

Variations of oil volume fraction have an impact on the viscosity and density of the mixture, which affects the flow conditions in the separator and further influences the separation process. The mixing system can be divided into two systems with the oil volume fraction is 0.5. When the

oil volume fraction is less than 0.5, the mixture is defined as oil droplets in the water system, and the water phase as continual phase; however, when the oil volume fraction is more than 0.5, water is the dispersed phase, and oil is the continuous phase. Figure 6 presents the contour plot of oil volume fraction at resident time $t = 900$ s, which provides sufficient residence time for the dispersed phase to reach its maximum separation efficiency. Figure 6 illustrates the contours of oil volume fraction for the fluid, after separation, for three different initial ϵ_o . In addition, since the separation process reached its maximum separation efficiency, Fig. 6 cannot show the effect of various initial ϵ_o on the separation process; therefore, the variation of y^* with t^* are presented in Fig. 7. As illustrated in Fig. 7, the transient location of y^* is slightly affected by the oil volume fraction. When the oil volume fraction ranges from 0.2 to 0.5 (oil droplets are dispersed in the water phase), an increased oil volume fraction requires more time for line 2 (top of the interface layer) to reach the same y^* location. The same trend applies to water droplets in a continuous oil phase (when the oil volume fraction range is 0.5 to 0.8). Also, when the oil volume fraction is 0.8, the mixture is defined as water droplets in a continuous oil phase, which means the dispersed phase (water) has a volume fraction of 0.2.

3.1.2 Effect of temperature

The operating temperature is also a major factor for oil/water separation, as it affects the thermophysical

Fig. 6 Contour plots of oil volume fraction: **a** $\epsilon_o = 0.2$, **b** $\epsilon_o = 0.5$, **c** $\epsilon_o = 0.8$

Fig. 7 Transient effect of oil volume fraction (ϵ_o) on liquid/liquid separation dynamics

properties of oil and water, such as density and viscosity. Four different operating temperatures between 20 and 50 °C are investigated. As illustrated in Fig. 8, increasing temperature increases initial separation speed by reducing the oil viscosity; hence, increasing the oil droplets rising velocity. However, in Fig. 8, the curves values overlap for $t^* > 0.4$. This phenomenon suggests that with enough

resident time, the oil/water separation efficiency is independent of temperature. According to droplet force balance, droplet diameter is the critical factor that controls the droplet rising velocity, which is independent of operating temperature. Therefore, the effect of temperature is not significant for the overall oil/water separation. The overlapped curves also indicated that when the resident

Fig. 8 Transient effect of temperature on liquid/liquid separation dynamics

time is 900 s, investigation cases 5 to 7 share the same oil volume fraction distribution as the Base Case. The oil volume fraction contour plot of the Base Case as shown in Fig. 6a.

3.1.3 Effect of pressure

Operating pressures of 101.325, 344.738, 689.476, and 10,134.214 kPa are investigated. Since the pressure distribution is the same in the horizontal direction, it only changes in the vertical direction; therefore, a cross-sectional area is selected to demonstrate the contour plot of pressures fields, as presented in Fig. 9. All four investigated cases present a similar pressure distribution trend that the bottom of the separator has the highest pressure, and the top has the lowest pressure. This is because the density of water is higher than the density of oil, as the maximum separation efficiency is approached, the water phase formed at the bottom, with a relatively higher pressure than the oil phase at the top. The effect of operating pressure on the separation process is presented in Fig. 10. The slope of the curves decreases with increasing operating pressure, which means that separation speed decreases

with pressure. As illustrated in Fig. 10, to reach the same height ($y^* = 0.3$), t^* needs to be 0.016 and 0.025 for the operating pressure of 101.325 kPa and 1034.214 kPa, respectively. This indicates that increased pressure can significantly increase the time to separate oil from water. The reason for increasing the separation is because a high pressure limits the oil droplet rising velocity. Also, the effect of pressure on separation declines as pressure increases. When pressure is over 689.476, the pressure effects on y^* can be neglected, which is confirmed by comparing the results of pressure 689.476 and 1,034.214 kPa in Fig. 10. The vertical distance between lines is reduced until they almost overlap with each other.

3.2 Correlation development

The numerical prediction results and the investigation of the relationship of the selected dimensionless groups are discussed in this section. The relationship between the dimensionless groups is determined under the same separation efficiency value at the outlet. The correlation is presented and analyzed using nonlinear regression on the x-y Cartesian coordinate system. Manual iterations are

Fig. 9 Contour plots of pressure distribution: **a** $P = 101.325$ kPa, **b** $P = 344.738$ kPa, **c** $P = 689.476$ kPa, **d** $P = 1034.214$ kPa

Fig. 10 Transient effect of pressure on liquid/liquid separation dynamics

performed to determine the coefficients in the general correlation relationship. The simulation data are analyzed and plotted to calculate the constants in Eq. (9).

3.2.1 Reynolds Number ($Re = \frac{h \cdot v \cdot \rho_m}{\mu}$)

Variations of the Reynolds number are created by varying the inlet velocity, density, and viscosity of the mixture. The viscosity is changed by using different oil volume fractions, as seen in Eqs. (10) and (11). The correlation development of Π_1 as a function of the Re is shown in Fig. 11. The exponent for the relationship between Π_1 and Re is 0.1915, with an R-squared of 0.9188. The Reynolds number has a direct correlation with the separator geometry design; thus, an increase in Re requires a separator with a larger length to height ratio.

The results shown in Fig. 11 indicate that the required separator size increases with Re . This behavior is in line with our expectation of the effect of Re on oil/water separation efficiency. As the Re number increases, i.e., the importance of the viscous force with respect to the inertial forces increases, the separation efficiency decreases. Therefore, a bigger separator is required to maintain the same separation efficiency. These results are only for low Re numbers, where the fluid is in the laminar region. For this small Re number, Rieber and Frohn [26] conducted a simulation study to analyze the droplet collision behavior. Collision frequency decreases with the increase of the Re number in this regime. One of the reasons for this phenomenon, according to [26], is that the initial kinetic

energy dissipates after the collision of the two droplets. These simulation results were also validated by the experimental study conducted by Qian and Law [27].

3.2.2 Euler Number ($Eu = \frac{P}{\rho_m \cdot v^2}$)

In this study, the correlation between separator geometric design and pressure is investigated based on the Euler number. The exponent of the correlation shown in Fig. 12 indicates that the operational pressure has a direct correlation with separator geometry, i.e., increasing the operating pressure requires a separator with a larger length to height ratio. The reason for this trend is that the Euler number is a dimensionless group that represents the ratio of pressure forces to inertial forces; thus, for a higher Euler value, a larger separator geometry is required to maintain the same separation efficiency. Luiz et al. [28] found a similar effect of Euler number on the hydrocyclone separator. In the study, to achieve the separation duty, the energy cost of the separator increases with an increase in Euler number.

Also, the new Euler number correlation presents a high accuracy; as shown in Fig. 12, the R^2 is 0.9055. According to the correlation, the value of n_2 is 0.235.

3.2.3 Weber Number ($We = \frac{h \cdot v^2 \cdot \rho_m}{\sigma_{o/w}}$)

The developed correlation of the Weber number presents a negative exponent with separator geometry, as illustrated in Fig. 13. The value of n_3 is -0.214 , with R^2 of

Fig. 11 The effect of Re number on separator geometry design **Fig. 12** The effect of Eu number on separator geometry design

0.9768. The negative exponent relationship means that the required separator size decreases with the Weber number. In an oil/water mixture, the surface tension determines the shape of oil droplets in the water. When a surface tension gradient is generated between interfaces, it increases the pressure in the space between them, which results in the increase of oil/water separation efficiency. Therefore, a separator with a smaller

length to height ratio is sufficient to maintain the same separation efficiency. In addition, according to the results in this study, when the Weber number is less than 3, the higher oil/water interfacial tension leads to greater droplet collision efficiency, which improves the separation efficiency and requires a separator with a smaller length to height ratio. The experiment of Jiang et al. [26] investigated the coalescence behavior of droplets. In

Fig. 13 The effect of We number on separator geometry design

Table 5 The comparison of two iteration values

Constants	First manual iteration		Second manual iteration	
	Exponent	R ²	Exponent	R ²
n ₁	0.1915	0.9055	0.4055	0.9807
n ₂	0.235	0.9788	0.2383	0.9968
n ₃	-0.214	0.9768	-0.232	0.9868

their study, they found that increasing the Weber number increases the coalescence efficiency, thus improving the separation efficiency. This, in turn, requires smaller separator size to maintain the same separation efficiency. The similar effects of Weber number on the droplet breakup process are also confirmed by Jain et al. [29]. Their study found that at a low range of Weber number ($We < 40$), droplet breakup speed is decreased with the increase of Weber number.

A second manual iteration is conducted to achieve better accuracy of the correlation. The values of n_1 , n_2 , n_3 , and C are determined with respect to the numerical simulation results. The correlations are listed in Table 5. The minimum value of R^2 increases by 8.3% to a value of 0.9807, which indicates a high accuracy of the correlation. To determine the value of C , the slopes of the correlation lines are combined with all the dimensionless groups with respect to x/h , as illustrated in Fig. 14. The final correlation developed in this study is

$$\frac{x}{h} = 0.3307 \cdot (Re)^{0.4055} \cdot (Eu)^{0.2383} \cdot (We)^{-0.232} \quad (14)$$

3.3 Correlation validation

Two new simulations for different conditions of oil/water multiphase flow are conducted, which is to validate the new correlation (Table 6). The validation range of the correlation is limited to the studied domain of the parameters and phase properties of oil and water. As illustrated in Fig. 15, the simulation results are close to the correlation's predicted values, with an average error of 1.7% and a maximum error of 4.38% between the two methods. In industrial applications, the new correlation developed in this paper, Eq. (14) provides new insights into separator design for various operating conditions as well as new insights into the operating conditions that will achieve high separation efficiencies.

4 Conclusions

A series of gravity-based, oil/water separation simulations were conducted to investigate the relationship between the geometric design of a separator and multiphase fluid density (ρ_m), multiphase fluid viscosity (μ_m), fluid velocity (v), surface tension between two phases ($\sigma_{o/w}$), and operating pressure (P), by using a dimensional analysis

Fig. 14 x/h versus the combined dimensionless groups **Table 6** Validation for simulation cases

Pressure (Pa)	Oil volume fraction ε_o	Mixture density ρ_m	Mixture viscosity μ_m
689,476	0.5	935	0.1441
1,034,214	0.8	897.2	0.2298

method. The CFD model was validated with experimental data based on this study, and then a parametric study was conducted. The simulation results reveal that oil volume has a complex effect on the separation process due to the different emulsion systems. Increased operating temperature increases the droplet rising velocity, but it does not change the overall separation efficiency. Operating

Fig. 15 Comparison of new correlation for separation dynamics with numerical predictions

pressure exerts a significant effect on the oil/water separation process, and the time needed for oil to separate from the water phase increases with the increase of pressure.

The results of the correlation presented in this work indicate that the theoretical minimum length of the separator increases with the Re number and Eu number; however, it decreases with We number. These correlation results are consistent since an increase in the Re number, and Eu number decreases the separation efficiency. Therefore, it requires a larger separator to keep the same separation efficiency. Conversely, when the We number is less than 3, a higher oil/water surface tension leads to greater droplet collision efficiency, improving the separation efficiency, and thus requires smaller separator geometry. Finally, a new correlation (Eq. 14) has been developed among the four dimensionless groups to predict the geometric design of separator. The new correlation developed in this paper can be used as a reference for separator geometry design to separate immiscible fluids with a wide range of fluid properties and operating conditions.

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