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Effect of Inlet Configurations on the Separation Efficiency of Free Water Knock Out Vessel

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***Abstract* -** The FWKO (free water knock out) vessel is a device that separates bitumen emulsion extracted from oil sands into water and oil. The separation occurs due to gravity settling, which is influenced by the density difference between the water and oil. The residence time of the bitumen emulsion inside the pressure vessel is therefore crucial. This can be increased by primary control of the flow from the inlet. In this study, the residence time and separation efficiency of water-oil separators with four different inlet configurations were compared by numerical analysis. The FWKO pressure vessel is a horizontal type with a wide interface for high separation efficiency, and a porous baffle is configured to reduce the sloshing phenomenon of the flow. The oil-water separator employed in this study has a flow rate of 60 BPD (barrels per day) and a value of 2.2 SOR (steam-to-oil ratio), and was designed in accordance with Stokes theory. The working fluids are water, oil and gas, and the finite volume of fluid (VOF) method was employed to simulate the gravity separation process due to density differences in multiphase flows. The FWKO pressure vessel model stabilizes over time, allowing for a steady-state analysis where the flow does not change over time. Therefore, a pseudo-transient analysis technique was used. Fluent by ANSYS was employed for the numerical analysis, and lattice dependence tests were conducted to ensure the efficiency of the numerical analysis. Based on these numerical simulation conditions, the internal flow characteristics, and separation efficiency of the four different FWKO inlet configurations were compared and analysed.

***Keywords*:** FWKO, Multiphase separator, Inlet configurations, CFD, Oil-water separator, Oil sands

1. Introduction

The potential of unconventional energy resources, such as oil sands and shale gas, has recently attracted increasing attention as a possible replacement for depleting fossil fuel energy sources. Among them, oil sands are expected to be stored underground about five times more than oil, and production is steadily increasing. Oil sands are highly viscous, and there are two main ways to produce them. The first method is mining, whereby oil sands within 50 metres of the surface are extracted directly from the ground. The second method is SAGD (steam-assisted gravity drainage), which involves injecting hot steam into oil sands in deeper layers in order to reduce their viscosity. The SAGD process comprises four stages: steam injection, primary separation, de-oiling and water treatment. The oil sands at depth are highly viscous, necessitating the injection of high-temperature steam for a prolonged period to create a bitumen emulsion fluid. Recently, ES-SAGD (Expanding Solvent-SAGD) process, which simultaneously injects high-temperature steam and an organic solvent, has demonstrated an improvement in productivity of approximately 60% compared to conventional methods. As this unconventional energy resource gains traction, oil sands production technologies continue to be developed. In particular, research into the SAGD process is important because the majority of oil sands deposits are located at depths of more than 50 metres below the surface. The bitumen emulsion, which is made fluid by the injection of hot steam, is extracted and transported to the initial separation process, where the main process unit used is FWKO. A bitumen emulsion is a mixture of water and oil that exists in two phases: one in which the water is dispersed in the oil and the other in which the oil is dispersed in the water [1]. The process of separating the bitumen emulsion into oil and water is achieved by cohesion and coalescence [2].

In the FWKO unit, the bitumen emulsion is separated into phases by density difference, with the oil and water being separated through a structured process. FWKO devices are categorised into horizontal and vertical types. Horizontal type separators require a larger installation space than vertical type, but have the advantage of high separation efficiency due to the large contact area. Horizontal FWKO units are widely used in practical processes, and various studies have been conducted to improve the separation efficiency of horizontal FWKO units. Kwon et al. [3] investigated the separation efficiency as a function of oil-water ratio, water cut, residence time, and the number and height of baffles in a horizontal FWKO vessel. Their experiments demonstrated the impact of baffles on separation efficiency. Kang et al. [4] conducted a numerical analysis of the internal flow and separation efficiency of a horizontal FWKO inlet vane as a function of curvature and aspect ratio. Othman et al. [5] conducted experiments to investigate the separation characteristics of water and oil in a horizontal pipe separator, including the water-oil mixing speed and water cut. Hong and Kim [6] attempted to modularise the system by connecting two horizontal FWKOs and compared the separation efficiency according to the connection angle of the two modularised FWKOs to derive the optimal head angle. Kim et al. [7] conducted a numerical analysis to investigate the impact of various inlet configurations, porous baffles, and modularisation on separation efficiency in FWKO. Their findings indicated that equipping the inlet configurations with a vane distributor and cyclone separator could enhance separation efficiency. Akpan [8] Described the flow characteristics of a gravity separator in a multiphase separation tank as a function of the flow characteristics and additional equipment. Frankiewicz and Lee [9] conducted a numerical analysis study to improve the separation efficiency by varying the inlet nozzle, flow distribution, and baffle configuration to reduce the sloshing phenomenon that causes the internal flow to oscillate. This study aims to investigate the internal flow characteristics and separation efficiency of FWKO inlet configurations by using numerical analysis techniques. In order to enhance the separation efficiency by prolonging the residence time within the vessel, primarily by regulating the flow of the inlet flow, the inlet configurations were designated as the crucial design parameter. The numerical simulation model was designed based on Stokes theory [10], with a flow rate of 60 BPD (barrels per day) and SOR (steam-to-oil ratio) of 2.2. The finite volume method, VOF (Volume of Fluid) was employed to simulate the gravity separation process due to the density difference between multiphase flows. The pressure vessel model employed the pseudo-transient analysis technique, which can be approached as a steady-state analysis since the flow stabilizes over time. The internal flow characteristics and separation efficiency of four different FWKO inlet configurations are compared and analysed based on the aforementioned numerical simulation conditions.

2. Numerical Analysis
2.1. Model description
The horizontal oil-water separator model employed in this study is depicted in Fig. 1. The vessel is equipped with a porous baffle, which serves to reduce the phenomenon of sloshing of the flow through the provision of an effective resistance. This has the effect of stabilizing the flow and enhancing the efficiency of separation. The hole diameter (d) of the porous baffle is 6.4 mm, and a total of 157 holes are spaced (l) of 25 mm apart.

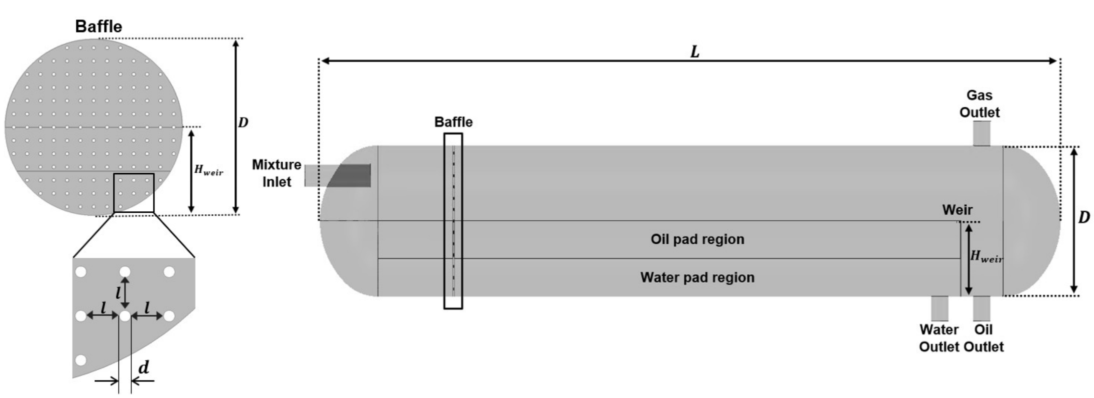

Fig. 1: Schematic of the modeled FWKO

where The baffle diameter (D) of the oil-water separator is designed to be 332 mm, while the length (L) is 1630 mm. The height of the weir is modelled to be 166 mm, which is half of the diameter of the oil-water separator. This is based on Stokes theory.

The flow rate of condensate W_{cl} (m^3/day) can be written as follows:

$$W_{cl} = C^{¿}\left(\frac{S_{hl} - S_{¿}}{\mu}\right) L_l A_l \tag{1}$$

where $C^{¿}$ is the experimental constant ($m^3 \cdot mPa \cdot s / m^2 \cdot day$) derived from the oil-water separator experiment. S_{hl} represents the specific gravity of the heavy liquid relative to water, while $S_{¿}$ denotes the specific gravity of the light liquid. The viscosity ($mPa \cdot s$) represents the viscosity of the continuous phase, $L_l(mm)$ is the length of the fluid interface, and the area of the fluid interface is $A_l(m^2)$ [11].

2.2. Inlet configurations

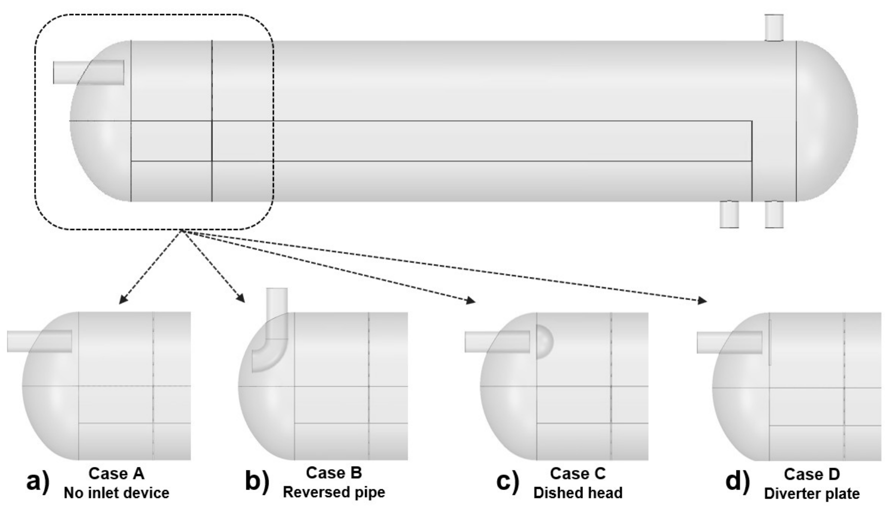

Fig. 2: Cases of inlet configurations

The configurations of the oil-water separator inlet configuration is depicted in Fig. 2 Cases A and B represent models without a separator plate, while Cases C and D illustrate models with a hemispherical, flat plate separator. The separator plate plays a pivotal role in regulating the flow from the inlet, and the working fluid can rapidly stabilize while losing its original fluid force, resulting in high separation efficiency. In order to facilitate a consistent comparison between the different cases, the distance between the inlet and the vessel wall in Case B was set to 15 mm, and the distance between the inlet and the separator in Cases C and D was also set to 15 mm. This ensured that the distance between the inlet and the vessel wall was identical for all cases, allowing for a more accurate and meaningful comparison.

2.3. Numerical analysis and boundary conditions

The working fluids employed were water, oil, and gas, and a multiphase analysis was conducted. Table 1 presents the physical properties of the working fluid and the surface tension between the phases. The L/D of the oil-water separation device was designed to be 4.9, and the boundary conditions of the inlet and outlet based on 60 BPD are presented in Table 2. The water and oil outlets were set to maintain a certain height by setting the pressure.

Table 1: Physical properties

Phase	$\rho[kg/m^3]$	$\mu[kg/(m\cdot s)]$	$\sigma[N/m]$
Gas	1.225	1.7894e-05	-
Oil	830	0.1	0.027 (with gas)
Water	998.2	0.001003	0.072 (with gas) 0.04 (with oil)

Table 2: Boundary conditions applied in this study

Boundary condition	Phase	Variables	Value
Inlet	Mixture	Velocity $[m/s]$	0.31056
Outlet	Air	Pressure [Pa¿	0
	Oil		677.44
	Water		1983.78

The governing equations employed in this study are as follows:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho U)=0 \tag{2}$$

$$\frac{\partial \rho U}{\partial t}+\nabla\cdot(\rho U\cdot U)=-\nabla p+\nabla\cdot\tau \tag{3}$$

The turbulence model was selected as the most widely used k-ε realisable model in multiphase separation analysis due to its optimal computational cost and performance. The Volume of Fluid (VOF) model was selected for the simulation of the gravity separation process due to the density difference between the multiphase flow and the necessity to track the continuous interface of the flow. Given that the FWKO pressure vessel model can be approached as a steady-state analysis in which the flow stabilizes over time and the flow does not change with time, the pseudo-transient analysis technique was employed. The numerical analysis was conducted using Fluent by ANSYS. To enhance the quality of the mesh, local refinement regions were incorporated in the vicinity of the inlet, outlet, and porous baffle, thereby increasing the density of the mesh. Inflation conditions were applied to guarantee the precision of the analysis. The mesh was constructed as a polyhedral mesh, and a GDT (grid dependency test) was performed on the Case A model to ensure the accuracy and efficiency of the numerical simulation. The GDT was conducted with the oil mass flow rate at the oil outlet according to the number of grids. The results demonstrated that the solution converged from 900,000 meshes. Consequently, a numerical analysis was conducted with approximately 900,000 grids for the four different models. Figure 3 illustrates the aforementioned findings.

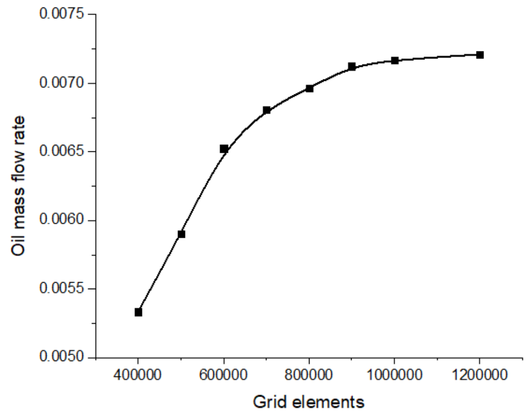

Fig. 3: Grid dependency test

3. Results and Discussion

3.1. Separation efficiency

A numerical analysis was employed to contrast the flow characteristics and separation efficacy of disparate inlet configurations of oil-water separators. The separation efficiency, which is the most important performance indicator of an oil-water separator, was calculated using the following equation: In Eq. (4):

$$\eta_{sep} = \frac{\dot{m}_{oil}}{\dot{m}_{oil} + \dot{m}_{H_2O}} \tag{4}$$

where $\dot{m}_{oil}$ represents the mass flow rate of oil discharged from the oil outlet(kg/s), while $\dot{m}_{H_2O}$ denotes the mass flow rate of water discharged from the oil outlet (kg/s).

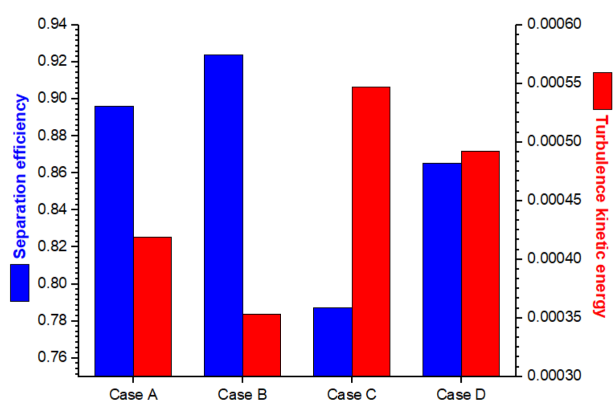

Fig.4: Oil-water separation efficiency and turbulent kinetic energy

The highest oil-water separation efficiency of 92.3% was obtained in Case B(reversed pipe type) without a separator, followed by 89.6% in Case A(dish head type) and 86.5% in Case D(diverter plate type) with a separator. The lowest oil-water separation efficiency of 78.7% was observed for Case C (no inlet type), a model with no separator plate and uncontrolled flow.

Fig. 4 depicts the average turbulent kinetic energy, which is calculated by making a vertical cross-section at the point where the flow passes through the porous baffle and stabilizes. The turbulent kinetic energy is a measure of turbulence intensity and was found to be inversely related to the oil-water separation efficiency. Based on these findings, a correlation was derived between turbulent kinetic energy and separation efficiency, which was defined as Eq. (5). This is also corroborated by previous studies [12].

$$\eta_{sep} = K \frac{1}{\phi_k} \tag{5}$$

where K is the correction factor, and ϕ_k is the turbulence kinetic energy, respectively.

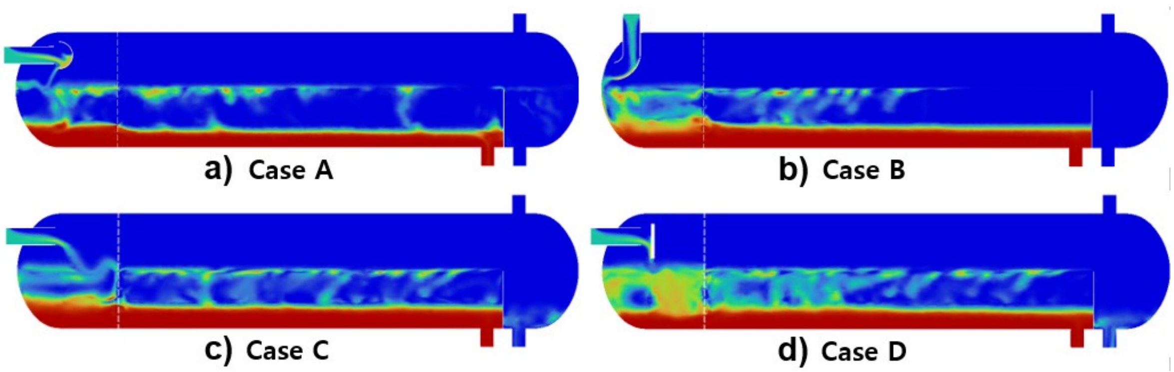

Fig. 5: Water contour of the oil-water separator cross-section at 120 seconds after the working fluid is enter into the inlet

Table 3: Residence time for different inlet configurations

	Case A	Case B	Case C	Case D
Residence time(s)	120.56	164.24	99.68	109.64

The water contour in the oil-water separator along the streamwise direction at 120 seconds after the working fluid enters is illustrated in Fig. 5. The time from the working fluid entering to the oil outlet is designated as the residence time and is presented in Table 3. In Case B, which exhibits the highest degree of separation efficiency, the working fluid has not yet reached the oil outlet at 120 seconds, and the residence time is the longest at 164 seconds. The second most efficient case, Case A, had a residence time of 120 seconds, while Case D had a residence time of 109 seconds. The least efficient case, Case C, without a separator, had the shortest residence time of 99 seconds.

3.2 Validation

Kwon et al. [3] conducted experiments on the water separation characteristics of oil-water mixtures in a horizontal FWKO vessel. In the experiment decane, toluene, and asphalt were used as model oils, and the separation efficiency of oil-water was investigated with experimental variables such as residence time and number of obstruction plates. The oil model employed in the numerical analysis of this study is engine oil, with a density of 830 $[kg/m^3]$ and a viscosity of 100 [cP]. In the experiment, Toluence was combined with asphalt, and the viscosity of the resulting mixture was set to 100 [cP] and measured using a rotational viscometer (Brookfield, LTV). At a 100 [cP], which is the same condition as the numerical simulation, the separation efficiency was between 83% and 88%, depending on the number of baffle plates and the residence time. Kwon et al. [3] observed that the separation efficiency increased due to the flow being controlled by the installation of baffles and the residence time of the internal flow increasing. Therefore, it can be concluded that the results of the present study are valid when compared with the existing experimental results.

As the residence time increases, the separation efficiency tends to increase. The discrepancy in residence time attributed to the inlet configuration is postulated to occur within the mixing zone prior to traversing the porous baffle. In Case B, the process of phase separation into water and oil occurred in the leftmost section of the inlet due to the resistance of the bitumen emulsion entering the inlet. In Case A, the process occurred in the middle of the mixing zone, while in Case D, it occurred in the rightmost section just before the porous baffle. In Case C, the working fluid was directed to the porous baffle without encountering any resistance. In conclusion, the alteration of the inlet configuration led to a divergence in the location of the phase separation zone, which in turn resulted in a discrepancy in the residence time. It could be resulted in a divergence in the separation efficiency.

4. Conclusion

The objective of this study was to enhance the separation efficiency of oil in a FWKO, a device that separates bitumen emulsion extracted from oil sands into water and oil. A horizontal FWKO with a capacity of 60 BPD was applied, and a porous baffle was constructed in order to reduce the occurrence of internal sloshing. Four distinct cases were devised, with the variables set as the configuration of the inlet device. ANSYS Fluent was employed for numerical analysis, and a VOF model was utilized to implement the gravity settlement method. In order to enhance the efficiency of the mesh, a lattice dependence test was conducted.

The numerical analysis demonstrated that the separation efficiency exhibited a variation of approximately 14% contingent upon the inlet configurations. The inlet directed to the left wall of the vessel (Case B) exhibited the highest separation efficiency 92.3%, while the inlet without a separator plate (Case C) exhibited the lowest separation efficiency 78.7%. The change in shape of the inlet configurations primarily controlled the incoming flow, which resulted in differences in the section where the phase separation process occurred. This resulted in a difference in the residence time of the working fluid inside the vessel, which in turn led to a 14% difference in separation efficiency.

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References

[1] Hong, J. H., Kim, B. S. and Kim, D. C., “Demulsification of Oil-water Emulsion by Microwave Irradiation,” *Korean Chemical Engineering Research*, Vol. 42, No.6, pp. 662~668, 2004.

[2] Wiley, R. M., “Limited Coalescence of Oil Droplets in Coarse Oil-in-water Emulsions,” *Journal of Colloid Science*, Vol. 9, No. 5, pp. 427~ 437, 1954.

[3] Kwon, S. C., Park, K. Y., Yoon, S. M., Kim, J. Y., Park, C. Y., Bae, W. S., and Rhee, Y. W. “Characteristics of water separation for oil-water mixture in a FWKO vessel,” *Korean Chemical Engineering Research*, Vol. 49, No. 6, pp. 823~828, 2011.

[4] Kang, J. Y., Lee, J. G., and Kim, Y. J., "Effects of the Change of Inlet Vane Configuration on the Separation Efficiency of FWKO," *Transactions of the Korean Society of Mechanical Engineers*, pp. 605-610, 2016.

[5] Othman, H. A., Dabirian, R., Gavrielatos, I., Mohan, R., and Shoham, O. “Validation and improvement of the horizontal pipe separator model”. In *SPE Western Regional Meeting,* (p. D041S007R001). SPE, 2018.

[6] Hong, C. K., and Kim, Y. J., "Numerical Study on the Inlet Head Configuration of Multi-Phase Separator for Modularization," *Transactions of the Korean Society of Mechanical Engineers - B*, Vol. 41, No. 9, pp. 571-577, 2017.

[7] Kim, H. J., Noh, H. J., and Kim, Y. J., "Effects of Design Parameters on the Performance of Multiphase Separator for Energy Plant," *Transactions of the Korean Society of Mechanical Engineers - B*, Vol. 43, No. 1, pp. 19-25, 2019.

[8] Akpan, D. G., "*Performance of internals in three-phase tank separators*" MS thesis. Institutt for petroleumsteknologi og anvendt geofysikk, 2013.
[9] Frankiewicz, T., and Lee, C. M., "Using Computational Fluid Dynamics (CFD) Simulation to Model Fluid Motion in Process Vessels on Fixed and Floating Platforms.*" Paper presented at the SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, pp. SPE-77494, 2002.
[10] Arnold, K., and Stewart, M., "Surface Production Operations, Volume 1: third Edition, Design of Oil-Handling Systems and Facilities," *USA:Gulf Professional Publishing*, 2008.
[11] Bahadori, Alireza., *Natural gas processing: technology and engineering design*. Gulf Professional Publishing, 2014.
[12] Prasad, R. RS., *One-step Process for Transforming a Water-in-oil Emulsion into an Oil-in-water Emulsion*. No. US 4627458. 1986.