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Numerical simulation of separation characteristics of separator guide plate for CO_2 flooding fluid

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Numerical simulation of separation characteristics of separator guide plate for CO_2 flooding fluid

Yu Li[1], Miao Yang[2,3], Zhibo Cao[1] and Jun Li[1]

[1] Infrastructure project department, Xinjiang oilfield company;
[2] College of Petroleum Engineering, Xi'an Shiyou University, Xi'an 710065, China.

[3]Email: 1169004952@qq.com

Abstract. In order to investigate the influence of the guide plate placement angle on the separation efficiency of CO_2 flooding fluid, the separation characteristics of the horizontal separator guide plate were simulated by using ANSYS Fluent. Fitted the physical parameters of CO_2 flooding fluid under the running condition of the separator, adopted the Mixture model of multiphase flow, and carried out the simulation of the guide plate placed at four placement angles (15°, 30°, 45°, 60°). The simulation results can provide a basis for designing a more efficient separator for CO_2 flooding fluid.

1. Introduction

In recent years, the research about the CO_2 oil displacement technology has attracted much attention. Because CO_2 has good fluidity, it can enlarge the volume of crude oil, reduce the viscosity of crude oil and reduce the interfacial tension of oil and water, which is an effective way to improve the oil recovery[1]. The results of the study show that CO_2 flooding can enhance oil recovery by 7% to 23%, with an average of 13.2%. Compared with other oil displacement technologies, CO_2 flooding has the advantages of large range of application, low cost and significant enhancement in oil recover. In 1950s, Whorton first obtain the patent of oil recovery by using CO_2, since then, as a method of secondary and tertiary oil recovery, CO_2 flooding technology has been extensively studied in laboratory and field[2]. Many oilfields have realized large-scale production by using this technology, and achieved good economic benefits[3-5]. As early as 2003, the Chinese government paid close attention to the capture, commercial utilization and storage technologies of CO_2[6], and more and more CO_2 flooding enhanced oil recovery projects have been carried out with the support of Chinese authorities and oil companies[7]. Practice has proved that CO_2 flooding technology is one of the most promising methods to enhance oil recovery during the process of tertiary oil recovery[8]. CO_2 oil displacement has positive significance for petroleum industry and environmental protection, and can achieve the unity of economic and social benefits, therefore, this technology will become a new direction of oil recovery technology development in the future.

Studies have shown that degassing causes varying degrees of foaming of the crude oil. Slight foaming can quickly dissipate in seconds. However, crude oils with high gas to oil ratio produce severe foaming when gas-liquid separation is performed. The surface treatment (separation, dehydration, etc.) of foaming crude oil has long been a problem, which has brought a lot of trouble to each stage of oilfield surface engineering, and oil foaming will cause some serious consequences to petrochemical process, such as: decrease in crude oil treatment,product disqualification, or the equipments abnormal operation, and effects on the treatment effect of oil, gas and water[9], and these conditions can bring great losses. Since its' high gas-liquid ratio, the CO_2 flooding produced fluid will be seriously foaming when gas-liquid separation is performed. The separation of gas and liquid is the key link of CO_2 flooding ground gathering and transportation process, which directly influences the follow-up treatment effect and the selection of relevant equipment and materials. Therefore, it is necessary to study the gas-liquid separation technology for the production of carbon dioxide flooding.

Mitohel Rooker has experimented with a variety of ways to destroy large volume wet foams, such as ultrasound, static electricity, etc., and finally found that the most cost-effective way is to provide an adequate residence time for the fluid in the separator. Thus, foams will disappear naturally as the process flows[10]. Based on the characteristics of heavy oil in Tahe No. 6 oil field, Zhang Ruihua has developed an oil gas separator for treating foamed crude oil[11]. The research of Zhaohui Chen analyzed the gas - liquid separation technology of foamed crude oil, and designed a separator for foaming crude oil[12].

Although considerable investigations on oil-gas separator have been developed over the past several years, the separation characteristics of the internal components of CO_2 flooding liquid separator have not been lucubrated. In this paper, a numerical analysis was applied. Based on the results of gas outlet liquid holdup, liquid outlet gas rate and Y - direction velocity distribution profile of liquid, the influence of flow deflector in separator on the separation efficiency of CO_2 flooding fluid was discussed.

2. Physical and mathematical models

2.1. Description of physical problem

In this paper, the separator suitable for separation of CO_2 flooding produced liquid is studied. The horizontal separator are selected and its' internal components are simulated and optimized by using the FLUENT software. The geometric three-dimensional model of the separator is established, and the separator is simplified due to its' complexity.

The main content of this paper is the guide plate in the separator. Inside the separator, the fluid will impact to the guide plate, then enter the liquid collecting zone. During the process, the guide plate can reduce the momentum of the gas and oil mixture. Guide plate can also play the role of washboard and inlet diverter. In this paper, in order to discuss the effect of the guide plate angle in the separation, simulation and optimization are carried out. Omitting components which won't be discussed, and the final figure 3D model of separator is illustrated in Figure 1.

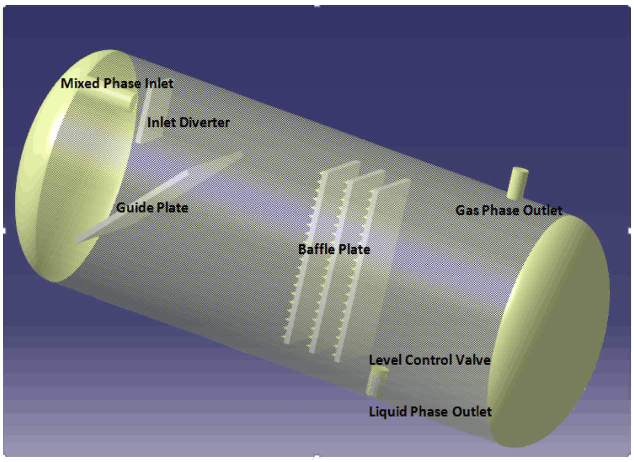


Figure 1. Figure 3D model of separator.

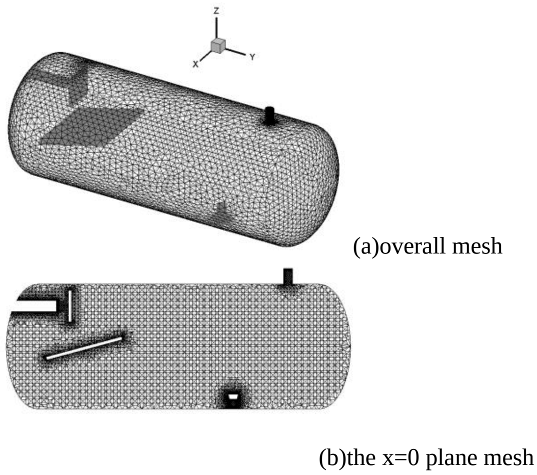


Figure 2. Mesh model of separator(guide plate 15°).

Table 1 illustrates the dimension of various parts of the separator.

Table 1. Dimension of various parts of separator.

Structure Name	Length(mm)	Width(mm)	Height(mm)	Diameter(mm)
Mixed phase Inlet	——	——	——	140
Inlet Diverter	400	400	40	——
Guide Plate	1000	1000	40	——
Baffle Plate	1200	600	40	——
Gas Phase Outlet	200	——	——	140
Liquid Phase Outlet	150	——	——	114

2.2. Mathematical model

2.2.1. Governing equations The fluid in the separator is a gas-liquid two-phase flow, which satisfies the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

The mass conservation equation is expressed as follow:

$$\frac{\partial}{\partial t}(\rho_m)+\nabla\cdot(\rho_m)\vec{v}_m = m \tag{1}$$

$\vec{v}_m$ denotes average mass velocity, is described as $\vec{v}_m = \frac{\Sigma_{i=1}^{2}\alpha_i\rho_i\vec{v}_i}{\rho_m}$; ρ_m denotes mixed phase density, described as $\rho_m = \Sigma_{i=1}^{2}\alpha_i\rho_i$; $\dot{m}$ represents mass increase.

The momentum conservation equation is expressed as follow:

$$\frac{\partial}{\partial t}(\rho_m\vec{v}_m)+\nabla\cdot(\rho_m\vec{v}_m\vec{v}_m) = -\nabla p+\nabla\cdot\left[\mu_m\left(\nabla\vec{v}_m+\nabla\vec{v}_m^{T}\right)\right]+\rho_m\vec{g}+\vec{F}+\nabla\cdot\left(\Sigma_{i=1}^{2}\alpha_i\rho_i\vec{v}_{dr,i}\vec{v}_{dr,i}\right) \tag{2}$$

$\vec{F}$ denotes the volume force; μ_m denotes the gas-liquid miscible dynamic viscosity, $\mu_m = \Sigma_{i=1}^{2}\alpha_i\mu_i$; $\vec{v}_{dr,i}$ denotes drift speed, $\vec{v}_{dr,i} = \vec{v}_i - \vec{v}_m$

The energy conservation equation is expressed as follow:

$$\frac{\partial}{\partial t}\left[\Sigma_{i=1}^{2}(\alpha_i\rho_iE_i)\right]+\nabla\cdot\Sigma_{i=1}^{2}\left[\alpha_i\vec{v}_i(\rho_iE_i+p)\right] = \nabla\cdot\left(k_{eff}\nabla T\right)+S_E \tag{3}$$

Where, k_{eff} denotes effective thermal conductivity, S_E is the volume heat source, it can be ignored in this system.

2.2.2. Turbulence model Turbulence models are very common in engineering practice, but because turbulence is very complex, turbulence models are usually established by simplification.

In this paper, the standard model of turbulence model is selected. The equations for the turbulent kinetic energy and dissipation rate of the standard model are as follows:

$$\rho\frac{dk}{dt} = \frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{4}$$

$$\rho\frac{ds}{dt} = \frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+G_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

Where,

G_k indicates that the turbulent kinetic energy due to the mean velocity gradient, $G_k = \mu_t\left[\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right)\right]\frac{\partial v_i}{\partial x_j}$; G_b is the turbulent kinetic energy caused by buoyancy, $G_b = \beta g_i\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial T}{\partial x_i}$;

β is the coefficient of expansion, $\beta = -\frac{1}{\rho}\frac{\partial P}{\partial T}$; g_i is the component of gravitational acceleration in the i direction; Y_M represents the effect of the total expansion of the compressible turbulent flow on the total dissipation rate, $Y_M = 2\rho\varepsilon M_t^2$, $M_t = \sqrt{\frac{k}{a^2}}$; $a = \sqrt{\gamma RT}$;Turbulent viscosity coefficient $\mu_t = \rho C_\mu \frac{\varepsilon^2}{k}$.

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are empirical constants, and their values in the FLUENT software are $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_{3\varepsilon} = 0.09$; $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$。

$\Pr_t$ is the turbulent Prandtl number ;

2.3. *Mesh model*

Unstructured grids are used for spatial discretization. Near the two phase flow inlet, inlet separator, guide plate, gas outlet, liquid outlet and liquid level control valve and other components the flow field changes in the violent, the grid near these components needs to be encrypted. Since the flow field region must be a connected closed region, a gap of about 1 mm is left between the liquid level control valve and the liquid outlet conduit. The overall mesh is shown in Figure 2 (a); the x = 0 plane of the three-dimensional mesh is shown in Figure 2 (b)

Meshing the other model with different guide plate angle, the number of grid cells for 15°, 30°, 45°, 60°guide plate is 707161, 703071, 692075, 704329; and the minimum mesh quality is 0.3.

2.4. *Solving condition*

2.4.1. Physical parameters The physical parameters of gas-liquid two-phase flow are obtained by using Unisim software, as shown in Table 2

2.4.2. Boundary condition In this paper, the gas phase is defined as the main phase; while the liquid phase is the second phase. The boundary conditions of each part of the separator are shown in Table 3.

3. Simulation results and discussion

Through the simulation study of the guide plates placed with different angles (15°, 30°, 45°, 60°), it is found that the change rules of the average volume fraction of the liquid phase at the gas outlet and the vapor volume fraction at the liquid phase outlet was similar, just the stability values are different.

Table 2. physical parameters of carbon dioxide flooding produced fluid in separator.

parameters	temperature(℃)	pressure (MPa)	Inlet gas volume flow(m^3/h)	Inlet liquid volume flow(m^3/h)
	32	5	3.6	1.4
Liquid density(kg/m^3)	Liquid viscosity(cP)	Gas density(kg/m^3)	Gas viscosity(cP)	Surface tension between two phase(mN/m)
930	0.58	95	0.0165	11.3

Table 3. Boundary conditions of each part of separator.

Part	Boundary type	numerical value	Remarks
Mixed phase inlet	velocity inlet	Gas:3m/s Liquid:2.8m/s	The velocity direction is perpendicular to the entrance direction. Turbulence is 5%, Hydraulic diameter is 0.14m
Guide plate, inlet separator, liquid level control valve	Wall	No-slip wall	
Liquid outlet	Pressure outlet	0Mpa	Turbulence is 5%, Hydraulic diameter is 0.114m
Gas outlet	Pressure outlet	0Mpa	Turbulence is 5%, Hydraulic diameter is 0.114m

3.1. The liquid content of gas outlet

Figure 3 shows the liquid content of gas outlet at different angles of guide plates.

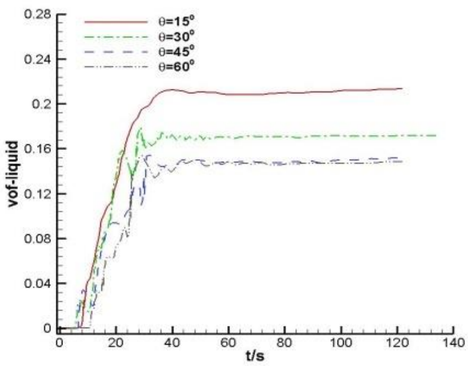


Figure 3. The liquid content of gas outlet.

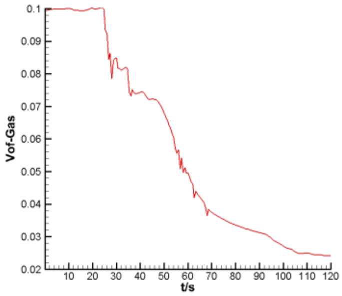
Taking the 15° guide plate as an example. As shown in Figure 3, during 0 ~ 8s, since the mixed fluid has just entered the separator, only gas flows out of the gas outlet; During 8 ~ 40s, the fluid slowly flows into the rear of the separator after an initial separation; as time goes on, the separated gas flows out of the gas outlet with a small amount of liquid; After 40 s, the liquid content of gas outlet tends to be stable. The average value of liquid holdup of gas outlet is 20.87% ; the value is 17.25% when the guide plate is placed at 30°; placed at 45°, the value is 15.92% ; and placed at 60°, the value is 14.82% .

It can be found that the more inclining the guide plate, the lower the liquid content of the gas outlet, and the reduced rate is decreasing. Since the higher the separation efficiency, the lower the liquid content, under the condition of the same conditions, the more inclined the deflector is, the more favorable for gas-liquid separation.

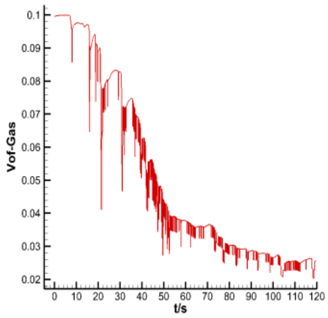
3.2. Gas content of liquid outlet

Figure 4 illustrates the change rule of gas content of liquid outlet at different angles with time. The overall trend is similar.

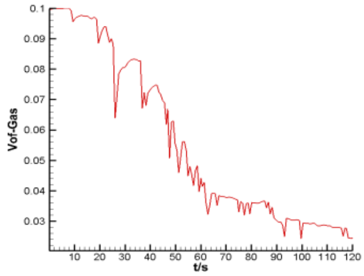
As shown in figure 3, before 25s, the fluid has just flowed into the separator, and has not disturbed the initial static fluid at the bottom of the separator yet, so the fluid flow out from the liquid outlet contains 10% gas. As time goes on, the mixed phase at the bottom of the separator began to be disturbed, because of inter phase slip, under the disturbance and the action of gravity, gas and liquid will be separated. The separated liquid will settle, while the gas will gradually rise to the gas-liquid interface. During this period, the components of the fluid at the bottom of the separator are in a dynamic change, and the general trend is a decrease in the gas content. After 110s, the gas content of liquid outlet turn to basically stable, and the average is 2.112%.



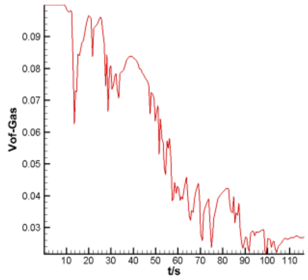
(a)Guide plate placed at 15 °



(b)Guide plate placed at 30 °



(c)Guide plate placed at 45 °



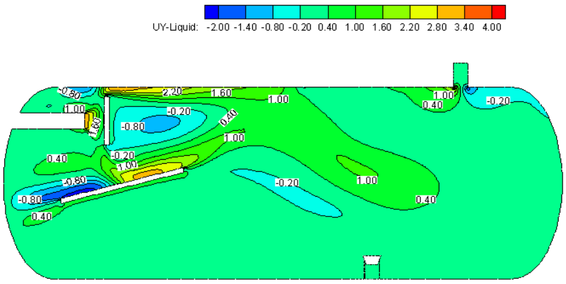
(d)Guide plate placed at 60 °

Figure 4. Gas content of liquid outlet.

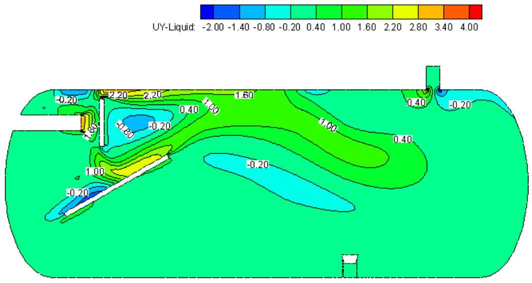
When the baffle plate is placed at 30°, 45° and 60°, the gas content of the liquid outlet is respectively: 2.551%, 3.152%, 2.896%. These values are kept at a low level, it can be considered that the placement angle of the guide plate has little effect on the gas content at the liquid outlet.

3.3. *Internal flow field of separator*

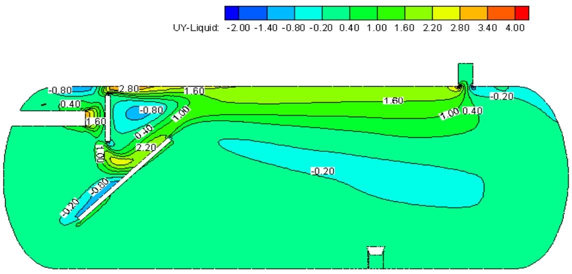
In order to analyze the variation of the flow field in the separator, the velocity profile of the liquid Y direction is drawn. When the separator is working, the liquid phase in the Y direction should be as small as possible, so that the fluid can stay longer in the separator and separated more thorough.



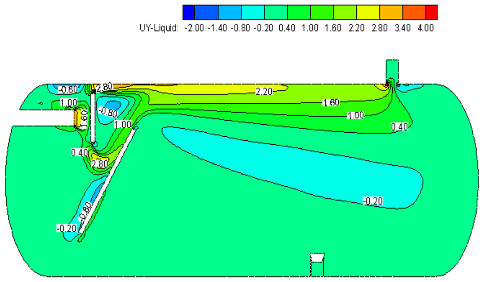
(a) Guide plate placed at 15 °



(b) Guide plate placed at 30 °



(c) Guide plate placed at 45 °



(d) Guide plate placed at 60 °

Figure 5. Y - direction velocity distribution profile of liquid.

The smaller the range of the contours of the liquids velocity in the graph, the more the negative velocity is, and the more favorable the separation is. When the Y velocity is in the range of -0.20~0.40, indicating liquid in these areas, Y direction velocity is approximately 0, which means only gas in this area or separation has completed; and the isoline density indicates that the fluid velocity changes violently here, which is not good for separation.

With the increase of the angle, the change intensity and range of velocity near the inlet diverter and guide plate is reducing. This shows that the large angle deflector is favorable for the separation of the mixed fluid in the front section of the separator, but when the guide plate is at 45°, the range of large velocity is similar to it's at the angle of 60°. The fluid enters the rear of the separator through the area between the guide plate and the inlet diverter, and the liquid phase velocity of this area increases with the angle of guide plate. From this point of view, the deflector placed at a large angle will be detrimental to the back separation.

In addition, when the fluid descends from the inlet diverter to the guide plate, the impact pressure is generated. The larger the guide plate angle, the greater the impact pressure, which will deteriorate the stability of the guide plate and shorten its life.

Considering Figure 3 and Figure 5, we can know that the higher the guide plate angle, the higher the separation efficiency, although the difference between 45° and 60° is not obvious. On the other hand, The large placement angle is not conducive to the long-term stable use of the guide plate. In short, taking various factors into account, the optimal placed angle is 45 degrees in this paper.

4. Conclusions

CFD simulation was carried out for the CO_2 flooding fluid separated through the horizontal separator using fluent software. Considering the complexity of the separator structure, unstructured grid was used to produce refined results with minimum error percentage. The main points of the paper are as follows:

The liquid content of gas outlet tends to reduce with increasing the angle of guide plate, that is to say, a larger guide plate angle is advantageous for gas-liquid separation.

The angle of the guide plate has little influence on the gas content at the liquid outlet

From the Y - direction velocity distribution profile of liquid, it can be obtained that the large angle guide plate facilitates the separation of the mixing fluid at the front section of the separator,but detrimental to the back section of separation.

In this paper, considering the various factors, 45°is the best angle of the guide plate for separating CO_2 flooding oil.

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