A fast and simple method for modeling of oil swelling in Co_2 injection

Jafar Vali [1]*, Ezatallah Kazemzadeh [1], Hessam Aloki Bakhtiari [1], Morteza Khodabakhshi [2], Mohammad Reza Esfahani [1]
[1] *Research Institute of Petroleum Industry (RIPI)*
[2]*Harold Vance Department of Petroleum Engineering Texas A&M University*
**Corresponding author, e-mail: valij@ripi.ir*

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Abstract

In this paper, the role of molecular diffusion in mobilization of waterflood residual oil is examined. A moving mesh method is applied to solve the moving interface problem of residual oil blobs swelling by Co_2 diffusion through a blocking water phase. The results of this modeling are compared with experimental results of a 2D glass micromodel experiment. Although, the solution method is applied for a 1D system, a good agreement between numerical and experimental results validates the solution method. In this method a fixed time step is proposed. Furthermore, the results of this method have been compared with the results of the Grogan's finite difference method. This supposed that, the mesh network is fixed and time step increasing will be continued until the oil-swelling equal to one spatial step size.

Key words: *Moving mesh, Moving interface problem, Oil swelling, Co_2 injection, Mathematical model.*

Introduction

The majority of oil fields are exploited by injecting water into the porous rock to displace the oil content. However, water flooding may leave behind as much as 60% of the oil originally in the reservoir (Dullien, 1992). Trapping of oil or other fluids are not understood completely. Green *et al.* mentioned that, the trapping mechanism depends on; pore structure of porous medium, fluid/rock interaction related to wettability, and fluid/fluid interaction reflected in Interfacial Tension (IFT) and sometimes in flow instabilities (Green, *et al.*, 1998).

Pore channels of reservoir rocks are not straight and smooth capillaries they are irregularly shaped channels. One phase may be bypassed by a second phase because of channel geometry. A simplified situation that exists in rock is shown in

Figure 1, which is based on an experimental study by Arriola *et al* (Green, *et al.*, 1998).

Injecting of gas, especially CO_2, is a proper approach to produce remained oil from water flooded zones. The displacement of oil due to CO_2 injection has been studied by some researchers (Campbell, *et al.*, 1985; Shelton *et al.*, 1975; Huang, *et al.*, 1974; Stalkup *et al.*, 1970), and considerable volume of experimental data now exists for the process(Campbell, *et al.,* 1985). In these studies, CO_2 usually displaces oil from a fully saturated slim tube or core test into a secondary position under conditions where phase behavior affects the development of miscibility. For these conditions, obtained recoveries were high and rate-insensitive, which provided that the effects of gravity segregation, viscous fingering, and bypassing are minimized.

The experimental studies, which were carried out on the effect of CO_2 diffusion to swell the oil, were done on a 2D glass micromodel (Campbell, *et al.*, 1985). Campbell describes an experiment in which oil in a dead-end pore was recovered by diffusion of carbon dioxide through a water-blocking phase. A schematic of this experiment is shown in Figure 2. Initially, oil in a dead-end pore (4mm diameter) was separated by a water barrier from flowing carbon dioxide stream. After a period of 26.5 hours the blocking water phase was completely displaced from the pore neck. As a result it is feasible to direct contact between the oil and carbon dioxide. The subsequent recovery of the oil was comparatively rapid (of the order of several minutes). The experiment was conducted at 25oC and 1200psia. Campbell's and also the other related experiments confirm the importance of diffusion and oil swelling in tertiary CO_2 displacement experiments. When the time is sufficient to allow for diffusion, the swelling eventually will be enough to break the water barrier that blocks the oil from flowing CO_2 channels.

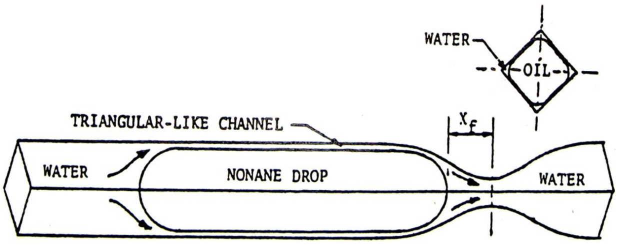

Figure 1: Trapping of nonane drops in square capillary constrictions (Green, *et al.* 1998)

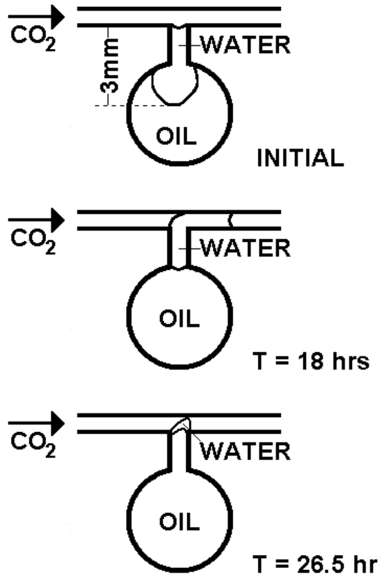

Figure 2: Campbell experiment (Campbell, *et al.,* 1985)

In contrast, for tertiary recovery experiments; where CO_2 is injected into a previously watered-out test core, recoveries of residual oil are observed to be considerably lower, dependent on both flood rate and core length, and different for water-wet and oil-wet systems. The differences between performance of secondary and tertiary flood experiments are usually explained in terms of the high water saturations present in the tertiary flood experiments and their effect on the microscopic displacement efficiency. As a consequence of the highly unfavorable mobility ratio for the immiscible CO_2 water displacement, injected CO_2 bypasses considerable volumes of water, leaving high water saturations behind the displacement front in water-wet rock. The water blocks or shields the residual oil from direct contact with the injected CO_2. This prevents development of miscibility and results a considerable reduction in microscopic displacement efficiency (Grogan, *et al.*, 1986; Shearn, *et al.*, 1978).

Theory

Molecular diffusion of CO_2 through the water-blocking phase has been suggested as an important mechanism in the mobilization and recovery of the residual oil in water-wet rock (Shelton *et al.*, 1975; Huang, *et al.,* 1974; Stalkup *et al.*, 1970). Swelling of the oil phase causes a breakdown in the original capillary equilibrium, due to pore-scale redistribution of the phases(Grogan, *et al.*, 1986). This process is fully effective in recovering residual oil when oil swells significantly. Recent flow visualization studies of two-dimensional micro models qualitatively confirmed the importance of diffusion and oil swelling in tertiary CO_2 displacement experiments. These studies have demonstrated clearly that the bulk of the water flood residual oil is left behind the CO_2 displacement front, trapped by water and therefore, cause to create inaccessible flowing CO_2 channels. Furthermore, it was observed that CO_2 diffusion through the blocking water phase causes to isolate oil droplets from water-wet rock due to oil swelling. When the time is enough to allow the diffusion, the swelling eventually will be enough to break the water barrier that blocked the oil from the flowing CO_2 channel and therefore, to obtain high oil recoveries.

Although, the available experimental data suggest that diffusion is important in the recovery of water flood residual oil, the role of diffusion and pore geometry parameters have not yet been quantified.

Therefore, it is not possible to scale the diffusion times and associated non-equilibrium state effects oil recovery in tertiary CO_2 floods in the laboratory or field.

The purpose of this paper is to apply a new solution method, which can be extensible to multidimensional systems to examine the role of molecular diffusion in tertiary recovery.

An idealized one-dimensional (1D) pore-scale model is developed that simulates CO_2 diffusion through a water barrier into a trapped oil phase and the subsequent swelling of the oil phase. The model clearly demonstrates the importance of diffusion in the recovery process. Computed concentration profiles are compared with available experimental data to validate the proposed model.

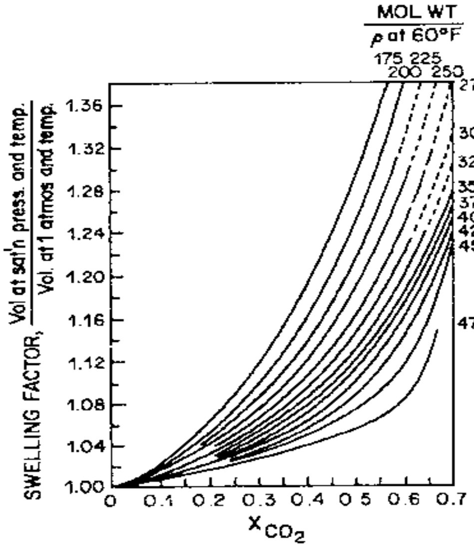

Figure 3: Swelling factor versus mole fraction (Bird, *et al.*, 1960)

When carbon dioxide is dissolved into a crude oil the volume of the oil increases. The amount of swelling depends on the pressure, temperature, crude oil composition and the mole fraction of CO_2 in the oil. Swelling data can be plotted in one of two ways:

as swelling factor versus mole fraction of Co_2 in the liquid phase

in the form of oil formation volume factor versus saturation pressure.

Error! Reference source not found. depicts data by Simon and Graue (Bird *et al.*,1960), which is particularly useful to predict the swelling factor where no measurements are available.

If, as a result of oil swelling, the change in the oil/water meniscus exceeds the range of radii possible for a given pore geometry, then the capillary equilibrium will be broken, and a subsequent phase rearrangement may result in oil mobilization. If the swelling phenomena cause to total displacement of the blocking water phase, direct contact between the oil and CO_2 affects phase behavior, which cause to high oil recovery. Whatever, in the actual mobilization mechanism, it is evident that the time required for diffusion to swell the oil is an important factor to determine the recovery efficiency of water flood residual oil.

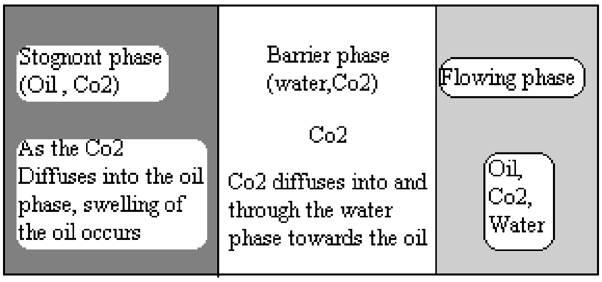

Figure 4: Simple model system for diffusion of CO_2 through a water-barrier phase1, (Huang, *et al.*, 1974)

The simplest model system that allows estimation of the diffusion time is shown in Figure 4. A confined or trapped oil phase is separated from a flowing CO_2-rich phase by an initially stagnant water barrier phase, and the diffusion process is assumed to be 1D. Because the solubility of CO_2 in both water and oil is considerably greater than the solubility of hydrocarbons in water and of water in oil, it may be considered the barrier and stagnant phases to be simple water/CO_2 and oil/CO_2 binaries, respectively (Shelton, *et al.*,1975; Huang, *et al.*,1974).

Diffusion causes the concentrating of CO_2 in the barrier and stagnant phases to increase with time, and the phases will swell. Typically, the oil will swell by 30% to 40% and the water by 2% to 7%. As a result of swelling, the oil/water and water/CO_2 interfaces move to the right hand side with time. For this analysis it assumes that the water/CO_2 interface remains fixed in its position; i.e., all the water that crosses this boundary is swept away by the flowing CO_2 phase. This simplification allows us to model the actual physical situation where the swelling of the oil displaces the water phase completely, allowing direct contact between the oil and CO_2 (breakthrough).

The solution of the partial differential equations describing the diffusion of CO_2 through the system with the appropriate boundary and initial conditions will yield the time required for breakthrough of the oil phase or for equilibrium conditions (maximum oil swelling) to be established. For a given crude-oil/water system, this time will depend on the length of the diffusion paths that exists in the actual porous medium.

Although the 1D model system considered is extremely simple, it simulates some features of tertiary mobilization of residual oil by CO_2 flooding.

Mathematical Model

Consider the situation shown in Figure 5. A liquid hydrocarbon phase, L, is in contact with a vapor phase. The vapor is soluble in the liquid phase, and the liquid may vaporize into the vapor phase. The physical analogue of this situation is the contact between a liquid hydrocarbon and a gas such as carbon dioxide, below the miscibility pressure.

The carbon dioxide will be dissolved in the hydrocarbon, resulting from the movement of the vapor liquid interface as the hydrocarbon swells.

Also, the hydrocarbon may be vaporized into the vapor phase. Both phases are considered to be binary mixtures of pure components or binary mixtures of pure component and a lumped pseudo component.

According to Fick's law[9], it is possible to write:

$$j_A = -\rho D_{AB} \frac{\partial w_A}{\partial x} \tag{1}$$

$$n_A = \rho_A v_A \tag{2}$$

Therefore, combination of equations (1) and (2) results:

$$n_A = -\frac{1}{1-w_A} \rho D_{AB} \frac{\partial w_A}{\partial x} \tag{3}$$

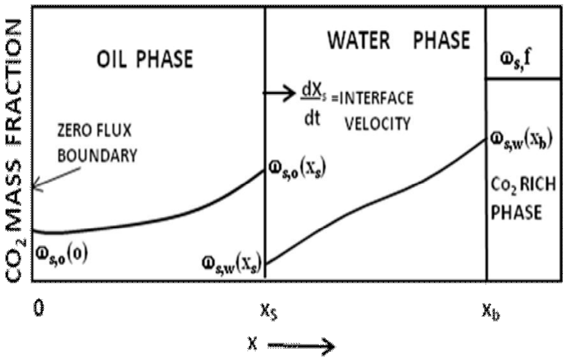

Figure 5: Contact of partially Miscible Fluid

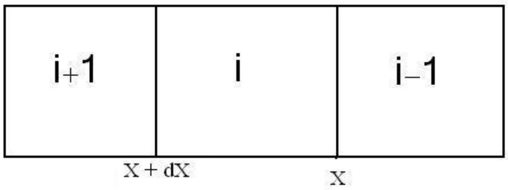

Figure 6: Schematic interior node

The continuity equation can be written as following general form:

(mass input)-(mass output) = (accumulative of mass)

From general form of continuity equation, it is feasible to write the following equation for nodes in one phase (oil or water) as follow (Figure 6):

$$n_A\big|_x . A\Delta t - n_A\big|_{x+\Delta x} . A\Delta t = A\left(\Delta x_i^{n+1} . \rho_{Ai}^{n+1} - \Delta x_i^n . \rho_{Ai}^n\right) \tag{4}$$

Using finite volume method for the equation (4) and substitute equation (3) in the left hand side of equation (4) yields:

$$-\left(\frac{\Delta t}{1-w_A} . \rho\right)^n_{ave\,(i,i-1)} D_{AB} . \frac{w^n{}_{Ai} - w^n{}_{Ai-1}}{\left(\frac{\Delta x_i + \Delta x_{i-1}}{2}\right)^n} +$$

$$\left(\frac{\Delta t}{1-w_A} . \rho\right)^n_{ave\,(i,i+1)} D_{AB} . \frac{w^n{}_{Ai+1} - w^n{}_{Ai}}{\left(\frac{\Delta x_i + \Delta x_{i+1}}{2}\right)^n} = \tag{5}$$

$$\rho_{Ti}^{n+1} . w_{Ai}^{n+1} . \Delta x_i^{n+1} - \rho_{Ti}^n . w_{Ai}^n . \Delta x_i^n$$

where

$$\rho_T = \frac{1}{w_{Ai} \upsilon_{AB} + (1 - w_{Ai})\, \upsilon_{BB}} \tag{6}$$

$$\left(\frac{\Delta t}{1-w_A} . \rho\right)^n_{ave(i,i+1)} = \left(\frac{\Delta t . \rho_{Ti}}{1-w_{Ai}} + \frac{\Delta t . \rho_{T(i+1)}}{1-w_{A(i+1)}}\right)^n \Big/ 2 \tag{7}$$

$$\left(\frac{\Delta t}{1-w_A}.\rho\right)^n_{ave\,(i,i-1)} = \left(\frac{\Delta t.\rho_{Ti}}{1-w_{Ai}} + \frac{\Delta t.\rho_{T(i-1)}}{1-w_{A(i-1)}}\right)^n \Big/ 2 \qquad (8)$$

It is clear that in each node, the mass (oil or water) is constant during CO_2 diffusion; only the CO_2 mass fraction changes; therefore, it can be written:

$$m_{Bi}^{n+1} = m_{Bi}^{n} \qquad (9)$$

Therefore, for right hand side of equation (5) it can be written:

$$A.\Delta x_i^{n+1}.\rho_{Ti}^{n+1}.\left(1-w_{Ai}^{n+1}\right) = A.\Delta x_i^{n}.\rho_{Ti}^{n}.\left(1-w_{Ai}^{n}\right) \qquad (10)$$

Rearrange the last equation yields:

$$\Delta x_i^{n+1}.\rho_{Ti}^{n+1} = \frac{\Delta x_i^n.\rho_{Ti}^n.\left(1-w_{Ai}^n\right)}{\left(1-w_{Ai}^{n+1}\right)} \qquad (11)$$

Before starting the simulation process, it assumed that all the spatial steps (Δx) have the same value. In the next time steps, because of occurring of oil and water swelling according to CO_2 diffusion, the amount of spatial step (Δx) may change at each node. This causes a variation in spatial position of nodes after each time step. Accumulation of these changes determines the total amount of swelling. Equation (5) and (11) result that:

$$-\left(\frac{\Delta t}{1-w_A}.\rho\right)^n_{ave\,(i,i-1)} D_{AB}.\frac{w^n{}_{Ai} - w^n{}_{Ai-1}}{\left(\frac{\Delta x_i + \Delta x_{i-1}}{2}\right)^n}$$

$$+\left(\frac{\Delta t}{1-w_A}.\rho\right)^n_{ave\,(i,i+1)} D_{AB}.\frac{w^n{}_{Ai+1} - w^n{}_{Ai}}{\left(\frac{\Delta x_i + \Delta x_{i+1}}{2}\right)^n} = \qquad (12)$$

$$\left(\frac{w_{Ai}^{n+1}}{1-w_{Ai}^{n+1}}\right).\rho_{Ti}^n.\left(1-w_{Ai}^n\right).\Delta x_i^n - \rho_{Ti}^n.w_{Ai}^n.\Delta x_i^n$$

The only unknown in this equation is w_{Ai}^{n+1}, which can be obviously determined with a simple arithmetic calculation. After calculating of w_{Ai}^{n+1}, it is possible to obtain Δx_i^{n+1} from equation (11) and equation (6).

Boundary Condition

Boundary conditions are as follow:

1- No flow boundary:

$$\frac{\partial w_A}{\partial x} = 0 \Rightarrow w_{A(i+1)} = w_{A(i-1)} \qquad (13)$$

2- Fixed concentration boundary:

$$w_{A(1)} = w_A^{sat} \qquad (14)$$

3- Interface equation:

There is no mass accumulation in the interface of oil and water, also an equilibrium conditions at each time exists at this point (Figure 7).

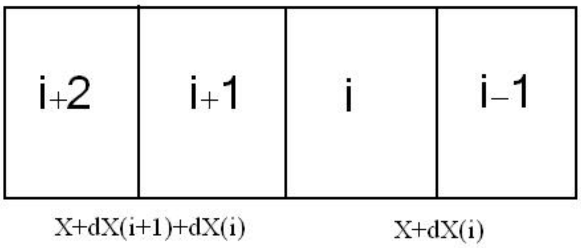

Figure 7: Schematic interface node

Therefore, for two continuous nodes at interface the following Equation can be derived:

$$-\left(\frac{\Delta t}{1-w_A}.\rho_{T-water}\right)^n_{ave\,(i,i-1)} D_{A-water}.\frac{w^n{}_{A(i)} - w^n{}_{A(i-1)}}{\left(\frac{\Delta x_i + \Delta x_{i-1}}{2}\right)^n}$$

$$+\left(\frac{\Delta t}{1-w_A}.\rho_{T-oil}\right)^n_{ave\,(i+1,i+2)} D_{A-oil}.\frac{w^n{}_{A(i+2)} - w^n{}_{A(i+1)}}{\left(\frac{\Delta x_{i+2} + \Delta x_{i+1}}{2}\right)^n} = \qquad (15)$$

$$\rho_{Ti-water}^{n+1}.w_{Ai}^{n+1}.\Delta x_i^{n+1} + \rho_{T(i+1)-oil}^{n+1}.w_{A(i+1)}^{n+1}.\Delta x_{i+1}^{n+1}$$

$$-\rho_{Ti-water}^{n}.w_{Ai}^{n}.\Delta x_i^{n} - \rho_{T(i+1)-oil}^{n}.w_{A(i+1)}^{n}.\Delta x_{i+1}^{n}$$

The mass transfer resistance in the flowing carbon dioxide rich phase is negligible in comparison to the diffusion resistance in the water and oil phases.

Therefore, the concentration of carbon dioxide in the flowing phase (CO_2) is considered as a constant. Equilibrium conditions are assumed at the water carbon dioxide interface and the water-oil interface. The carbon dioxide compositions on each side of the carbon dioxide-water interface (X_b) and the water-oil interface (X_s) are related by the equilibrium conditions:

$$w_{CO2(1)} = k_{CO2-Water} . w_{CO2} \quad \text{at } \mathrm{x = x_b} \tag{16}$$

and

$$w_{CO2(oil-interface)} = k_{Oil-Water} . w_{CO2(water-interface)} \quad \text{at } \mathrm{x = x_S} \tag{17}$$

where

$K_{CO2-Water}$ is the solubility of CO_2 in water at the prevailing conditions and $K_{Oil-Water}$ is the water/oil CO_2 partition coefficient. The oil phase is bounded by a no-flow (zero flux) boundary at $x = 0$. Combining equations (11), (15) and (17) results:

$$\begin{aligned}
&-\left(\frac{\Delta t}{1-w_A} . \rho_{T-water}\right)^{n}_{ave\ (i,i-1)} D_{A-water} . \frac{w^n_{A(i)} - w^n_{A(i-1)}}{\left(\frac{\Delta x_i + \Delta x_{i-1}}{2}\right)^n} \\
&+\left(\frac{\Delta t}{1-w_A} . \rho_{T-oil}\right)^{n}_{ave\ (i+1,i+2)} D_{A-oil} . \frac{w^n_{A\,(i+2)} - w^n_{A\,(i+1)}}{\left(\frac{\Delta x_{i+2} + \Delta x_{i+1}}{2}\right)^n} = \\
&\left(\frac{w^{n+1}_{Ai}}{1-w^{n+1}_{Ai}}\right)_{water} . \rho^{\,n+1}_{Ti-water} . \Delta x^{n+1}_i + \left(\frac{k_{oil-water} . w^{n+1}_{Ai}}{1-k_{oil-water} . w^{n+1}_{Ai}}\right)_{oil} \\
&. \rho^{n+1}_{T(i+1)-oil} . \Delta x^{n+1}_{i+1} - \rho^n_{Ti-water} . w^n_{Ai} . \Delta x^n_i - \rho^n_{T(i+1)-oil} . w^n_{A(i+1)} . \Delta x^n_{i+1}
\end{aligned} \tag{18}$$

The only unknown in this equation is w^{n+1}_{Ai} (CO_2 mass fraction in water phase at interface), which can be obviously determined. After calculating w^{n+1}_{Ai}, it is possible to obtain $w^{n+1}_{A(i+1)}$ (CO_2 mass fraction in oil phase at interface) from Eq.17.

Results and Discussion

Figure 8-11 a length of 9^{mm} was chosen for the Initial oil zone since this places similar volumes of oil in the model and the experimental systems. The model parameters -which are approximate- used in the calculation are given in Table 1. The computed time for oil swelling to completely displace the blocking water phase is approximately 22 hrs. In view of the approximate nature of the estimates used in the simulation, there is an encouraging agreement with the experimentally reported time of 26.5 hrs.

The difference between the computed and experimentally reported times may be explained by the approximate nature of the parameters estimated in Table 1 and the difference between the one-dimensional computation and the essentially two-dimensional nature of the oil-phase diffusion in the experiment. For the conditions of the experiment, the computation shows that the bulk of the mass transfer resistance occurs in the water phase, in which diffusion is essentially one-dimensional, and therefore, consistent with the numerical mode.

There is a good agreement between figures 8-11 and 12. Which, according to the Grogan's result (Figure 12) for this case, it is evident that the moving mesh method has the same accurate and more rapidly answer in spite of its simplified form relative to Grogan's model. The total time for the process is estimated 22 hours.

Table 1: Campbell experimental data

Parameter	Value
D_{CO_2-Oil}	$4.5\times10^{-9}\ m/s^2$
$D_{CO_2-Water}$	$1.95\times10^{-9}\ m/s^2$
$K_{Water-Oil}$	4.5
w^{sat}	0.058
$\upsilon_{CO2-oil}$	$0.0014\ m^3/Kg$
$\upsilon_{oil,oil}$	$0.0014\ m^3/Kg$
$\upsilon_{CO2-water}$	$0.0014\ m^3/Kg$
$\upsilon_{w,w}$	$0.0010\ m^3/Kg$

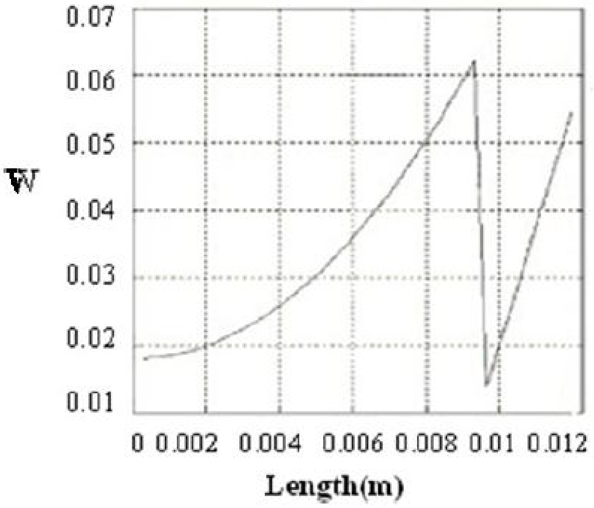

Figure 8: Computational CO_2 concentration profile after 2 hours.

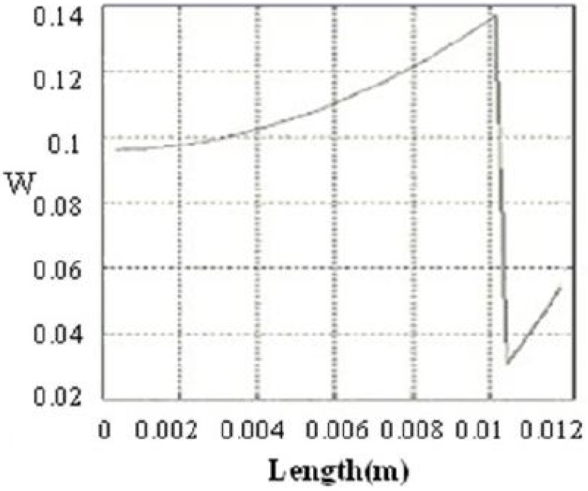

Figure 9: Computational CO_2 concentration profile after 7 hours.

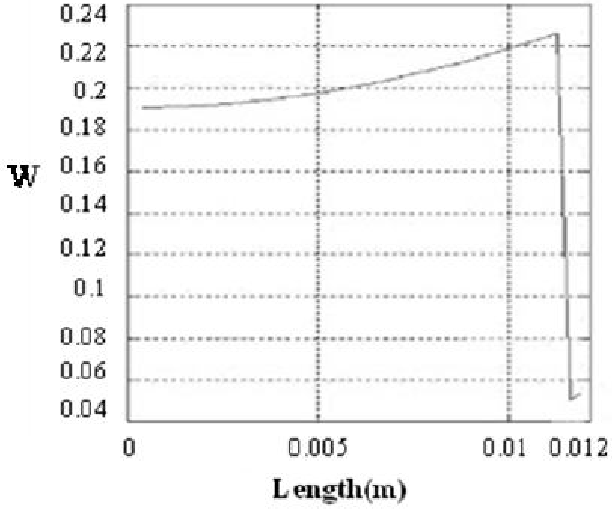

Figure 10: Computational CO_2 concentration profile after 15 hour

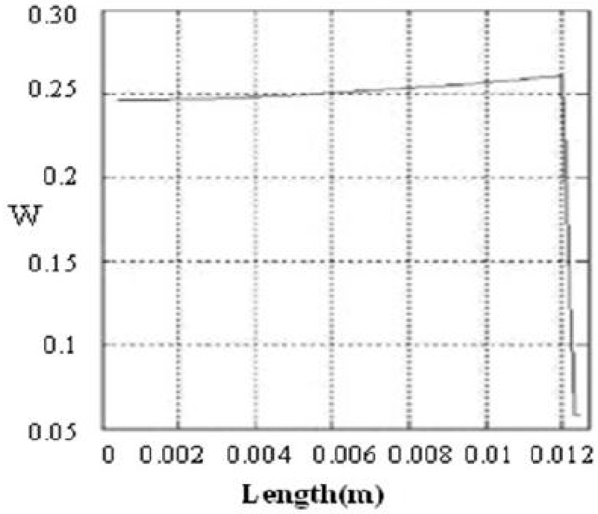

Figure 11: Computational CO_2 concentration profile after 22 hours.

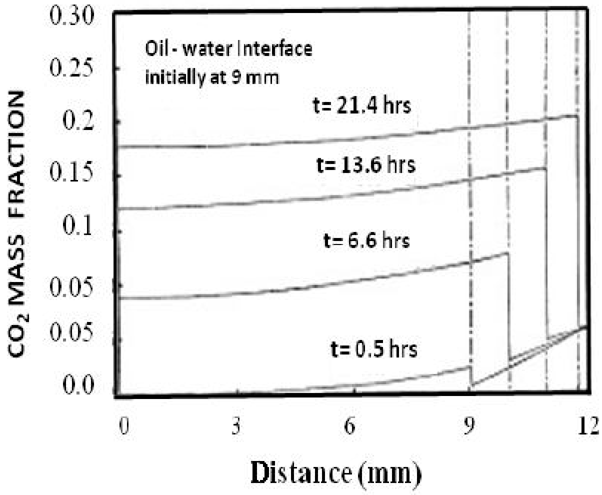

Figure 12: Grogan's computational results

Conclusion

The final achievements of this study are as below: It is feasible to direct contact between the oil and carbon dioxide and it is evident that the moving mesh method is the same accurate and more rapidly answer in spite of its simplified form relative to Grogan's model. The moving mesh method is not only a simple and fast method, but it can be extended to 2D and 3D systems

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