

Effect of Fracture Spacing on VAPEX Performance in Heavy Oil Fracture Systems

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ABSTRACT: *The vapor extraction (VAPEX) process, a solvent-based enhanced oil recovery process has been found promising for some heavy oil reservoirs. In this work, the VAPEX process is studied using a compositional simulator on a number of single-block and multiple block fractured systems. PVT data of one of an Iranian heavy oil reservoir are used to tune the equation of state. Effects of fracture spacing on the performance of process were studied. It was found that the fracture network enhances the VAPEX process in low-permeability systems by increasing the contact area between solvent and oil contained in the matrix blocks. Also, the fracture network reduced the instabilities in the system pressure and damped pressure surges in the system during the VAPEX process. In addition, results showed that solvent traverse between fracture network delayed the onset of solvent breakthrough and provided more residence time for the solvent to be in contact with heavy oil. In other part, effect of well location on the performance of process was studied. It was found that the oil production decreased as the well spacing increased. When the injection and production wells were far from each other, the oil production was governed by displacement for quite a long time rather than the gravity drainage enhanced by the VAPEX process. Also, improper location of the injection and production wells may results in the shortcut between injector and producer, which would lead to early solvent breakthrough and increased gas production through the system. The well location is a critical issue when applying the VAPEX process in fractured systems.*

KEY WORDS: *VAPEX, Heavy oil, Fractured reservoir, Well spacing, Fracture network.*

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INTRODUCTION

The increasing global demand of oil and diminishing trends in conventional (light and medium) oil reserves have led the researchers and oil companies to focus on the exploration and production of heavy and extra heavy oil reserves. Due to the decline of conventional oil reserves and high oil price in recent years, oil companies pay more attention to exploring heavy oil and bitumen fields. These huge resources estimated to be 4800 billion barrels (Gbbbl) in place [1] are important energy sources for the next decades. Heavy oil and bitumen are characterized by their high viscosities and low-degree API gravities (Fig. 1). The huge worldwide heavy oil reserves are reliable energy resources for the future. However, these reserves require application of enhanced oil recovery (EOR) processes to reduce oil viscosity and mobilize the oil contained in the reservoir in order to facilitate oil production.

The vapor extraction (VAPEX) process, introduced by *Butler* and *Mokrys* [2] as an alternative in-situ EOR method to Steam-Assisted Gravity Drainage (SAGD), has been studied theoretically and experimentally in conventional, non-fractured systems [2-8]. Basically, this process involves diffusion of vaporized solvent, mainly propane and butane into heavy oil. As a result, viscosity of heavy oil decreases and the mobilized oil flows towards producer by the mechanism of gravity drainage. Theoretical and experimental works on this process have shown promising results, and the VAPEX process can be regarded as an EOR method alternative to thermal processes [9].

Previous simulation studies on the VAPEX process in fractured systems [10,11] included single-block and multiple-block systems in which matrix blocks were surrounded by fracture networks. Results of these studies showed that the fracture network provides large area for solvent to distribute in the reservoir. This can be encouraging in application of the VAPEX process in low-permeability carbonate reservoirs, where the fracture network provides potential flow paths for solvent flow into reservoir.

In general, fractures are likely to enhance the process by improving the contact between solvent and oil contained in the matrix blocks. This is shown in Fig. 2 schematically for a matrix block surrounded by side, top, and bottom fractures.

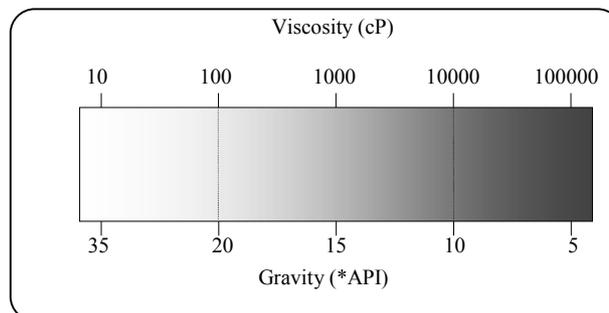


Fig. 1: Heavy oil classification [1].

According to this Fig., the solvent flows and diffuses from all sides into matrix, rather than just through a horizontal well. More over, the cross flow of solvent and upgraded oil provides additional contact points between oil and solvent. Also, fractures are likely to enhance the process by increasing the overall vertical permeability in the system. The important concern in this process when applied to fracture reservoirs is early solvent breakthrough through fracture network without efficient contact with heavy oil, which can reduce process efficiency and let the solvent escape out of the reservoir. Presence of thief zones in the reservoir can also affect the process, in that the solvent will flow out of reservoir without sufficient contact with heavy oil.

In this work, the effect of fracture network on the performance of this process is studied by simulating this process in a number of models. Effect of fracture network and fracture spacing on the damping the early time pressure surge, distribution of solvent in reservoir, oil production (rate and cumulative), onset of solvent breakthrough, and cumulative gas production are studied and discussed. Also, the performance of process is studied with different locations of injection and production wells and spacing between them in the model.

SIMULATION OF VAPEX IN FRACTURED SYSTEMS

Description of the Model

In order to study the performance of the VAPEX process in a system containing fracture network, a set of simulations were conducted on four fractured systems. The rock and fluid properties were the same in all models. Also, hydrocarbon pore volumes of all models were the same. The matrix and fracture permeability is set to 10 md and 10,000 md, respectively. The difference

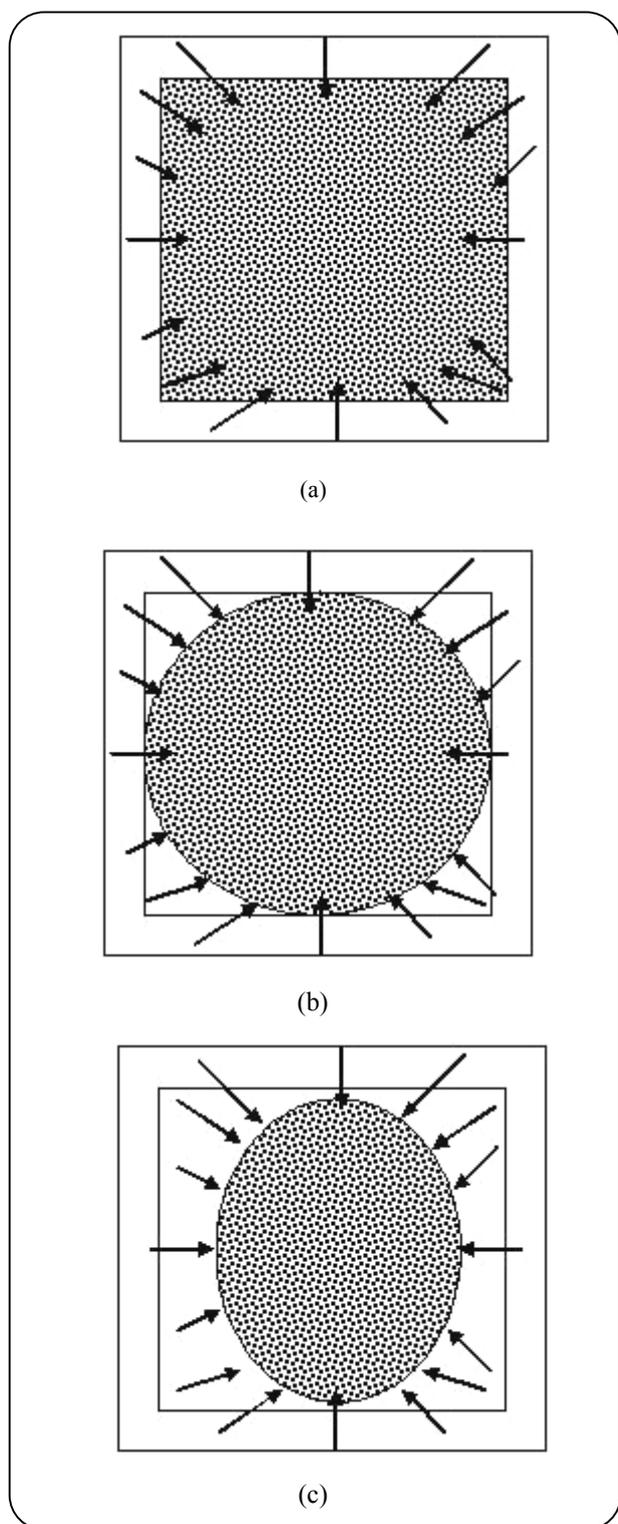


Fig. 2: Schematic representation of solvent and heavy oil diffusion and flow in a fractured system. a) early solvent diffusion; b) extended surface area for solvent diffusion; c) counter-current flow of solvent-heavy oil. The downward arrows indicate the oil flow.

between these models is the extent of fracture network in the system and fracture spacing, as shown in Fig. 3. In the first model, only one block is surrounded by fractures. In the second model, 9 blocks are surrounded by fracture network. In the third model, 25 blocks are surrounded by fracture network. Finally, the fourth model has 49 blocks surrounded by fracture network. As the number of blocks increase, fracture spacing decreases. Also, the number of matrix blocks is taken odd in order to prevent direct communication between injector (at the top) and producer (at the bottom). In three models that will be discussed later, the locations of injector and producer are changed, in order to investigate the effect of well location.

In developing the models, it is assumed that a very thin layer surrounds the rectangular model constructed in the previous section and treated as the conventional reservoir. The model is based on developing the dual porosity model by using the single porosity pattern to view the performance of process in the single block model more clearly. The simulator used in this study is CMG-version 2003 from computer modeling group [12]. Thermodynamic and phase behaviour data, as well as equation of state tuning are handled by the Winprop module of CMG. Also, the compositional simulations in this study are performed using the GEM module, which is the CMG's advanced general equation-of-state compositional simulator. CMG simulator has been successfully applied to the VAPEX process by other investigators such as *Nghiem et al.* [13], *Cuthiell et al.* [14], *Dauba et al.* [15], and *Das* [16].

The model dimensions are set to 0.89 ft by 0.89 ft by 0.04 ft. Other model properties are summarized in table 1. The reservoir properties of matrix are taken uniform and homogeneous. Effect of heterogeneities on the results and performance of the process is beyond the scope of this work. One injector is located at top center of the model and one producer is employed right below it at the bottom of the model.

The system pressure and temperature are set at 1000 psia and 21 °C, respectively. The crude oil used in simulations is taken from the Soroosh oilfield, which has a viscosity of 500 cp at atmospheric condition and its dead API gravity equals to 19. The Peng-Robinson Equation of State (PREOS) [17] is used in the simulations. Pressure, volume, temperature (PVT) data for the oil, such as oil formation volume factor,

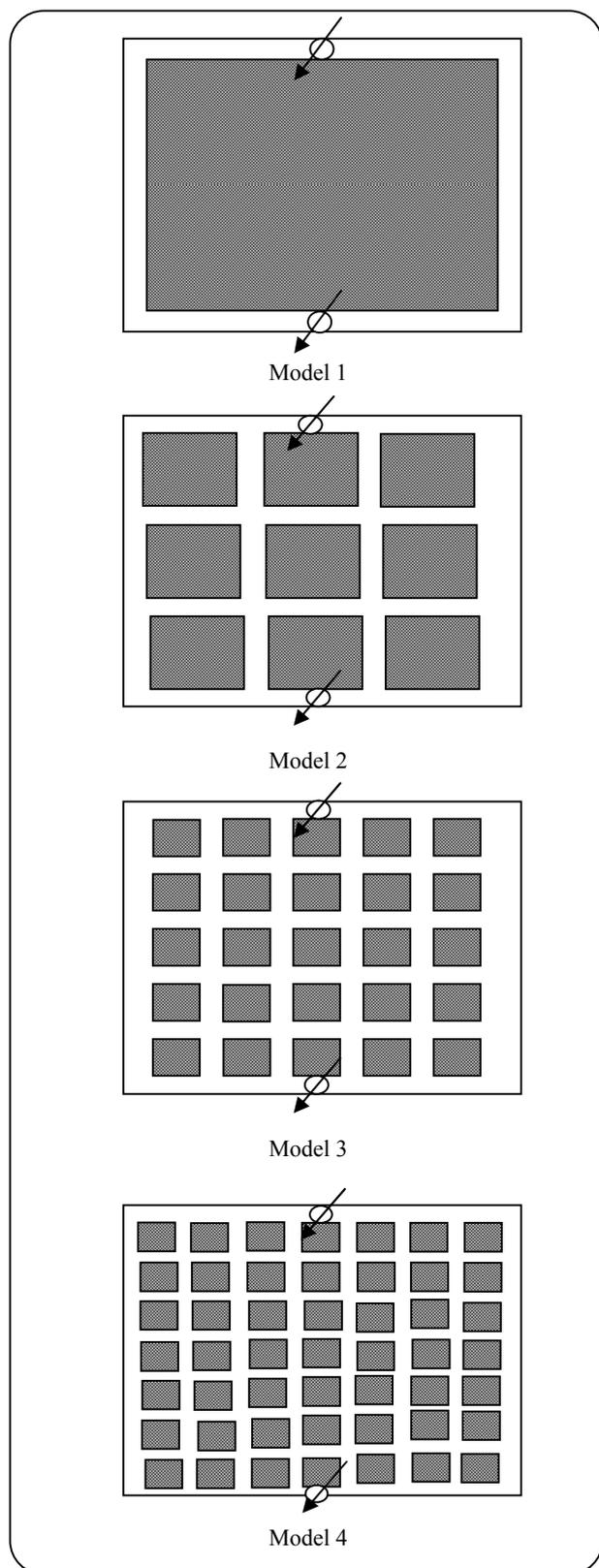


Fig. 3: Four different models used to study the effect of fracture network on the performance of the VAPEX process.

relative volume, oil specific gravity, oil viscosity, gas compressibility and gas-oil ratio are used to tune the EOS. Results of oil property prediction after EOS tuning and regression are given in Figs. 4-6 for oil specific gravity, relative volume, and viscosity, respectively.

The vapor pressure of the oil is 3000 kPa (433 Psia) so there is no free gas in the model according to the constant operating conditions at all stages of the process, as the operating condition is located above the bubble point at all times during the simulation. Thus, the model can be regarded as an under-saturated reservoir.

As there are too many components in the specified oil, lumping of the components is necessary in order to reduce the CPU time and simulation errors. The lumped oil system used in the simulations is shown in table 2.

The criterion that should be met in selecting the solvent system is that it should be at or near to its saturation (or, in the case of solvent mixtures, dew point) conditions. This criterion should be met in order to avoid any liquefaction of the solvent before it dissolves into heavy oil [18], as this may cause higher solvent consumption, which results in higher oil production costs. Moreover, as the vapor pressure of solvents (propane or butane) is very low at the specified reservoir conditions, liquefaction of the solvent in the high pressure reservoir is inevitable. To avoid this, the solvent should be mixed with a suitable non-condensable gas such as methane in order to reach the dew-point state under reservoir conditions. Different solvent mixtures were tested to find the best system which meets the aforementioned criterion. Fig. 7 shows the 2-phase P-T diagram for this system, where the compositions are 75 mole percent methane (C_1) and 25 mole percent propane (C_3). It is clear from this figure that reservoir conditions fall on the dew point curve, which meets the required criterion. If the operation conditions fall within the PT diagram, two-phase solvent will be injected into reservoir, which is undesirable.

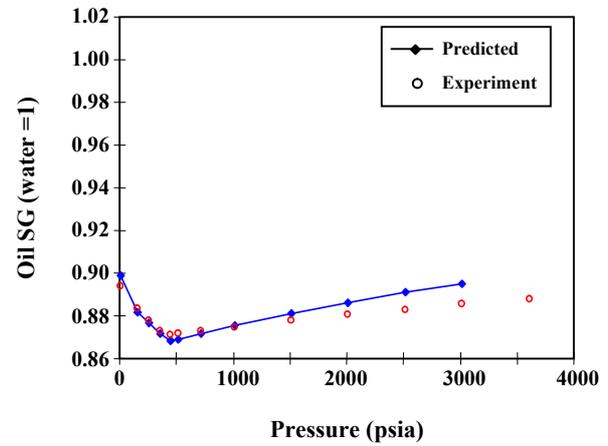
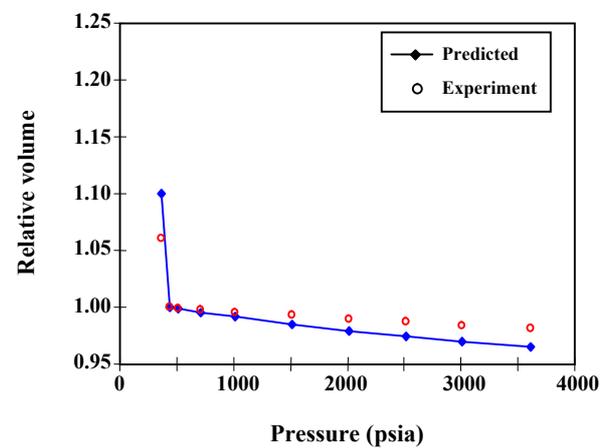
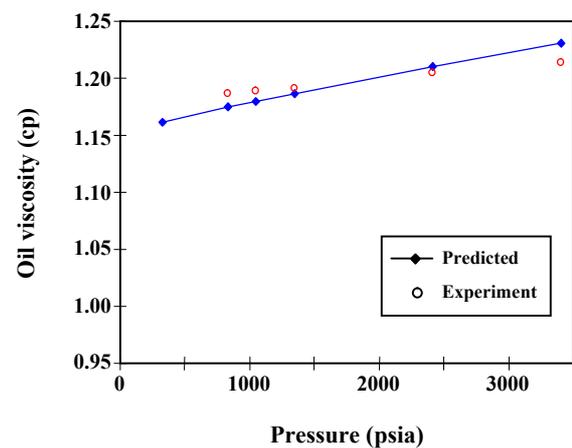
The relative permeability curves for matrix and fracture, used in numerical simulation studies, are shown in Fig. 8. The relative permeability curve of the matrix indicates an irreducible water saturation of 20 % and the residual oil saturation of 20 %. The relative permeability curves for the fractures are considered as straight lines with 45° angles. This assumes that the fracture system is approximately equivalent to a bundle of tubes, where the

Table1: Data for initializing the fractured model.

Grid type	Cartesian
Length in X-direction	0.89 ft
Length in Y-direction	0.89 ft
Length in Z- direction	0.04 ft
Matrix Porosity	0.3
Fracture Porosity	0.99
Matrix Permeability	10 md
Fracture Permeability	10000 md
Number of pseudo component EOS	8
EOS	PR(1978)
Temperature	21 °C
Initial pressure	999.3 psi
Initial oil viscosity	500 cp
Initial water saturation	0.2
Residual oil saturation	0.2
Number of injection well	1
Number of production well	1
Solvent injection composition	75 % C ₁ + 25 % C ₃ (mole %)

Table2: The lumped oil system used in the simulations.

Component	Composition (mole fraction)
N ₂	0.00187
C ₁	0.09471
CO ₂ - C ₂	0.05465
C ₃	0.06893
iC ₄	0.01055
nC ₄	0.02506
nC ₅ to C ₆	0.04973
C ₇ to C ₃₃₊	0.6945

**Fig. 4: Specific gravity of Soroosh heavy oil at 25 °C.****Fig. 5: Relative volume of Soroosh heavy oil at 25 °C.****Fig. 6: Viscosity of Soroosh heavy oil at 25 °C.**

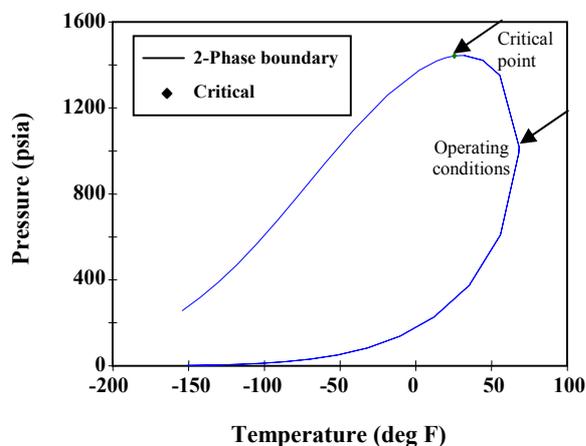


Fig. 7: Phase Diagram for C_1 (75 %) + C_3 (25 %) solvent system.

irreducible water and residual oil saturations are equal to zero [19].

The dual porosity model used in this study provides an efficient tool for visualization of the changes in the composition of system with time. This approach is a conventional method for simulation of fractured systems [20].

A comprehensive grid sensitivity analysis was performed to access the best grid size of model with little changes in oil rates and minimized numerical dispersion. The grid size and Δt scales selected in this work were the best ones. Equal pore volumes of solvent mixture were injected into three models, and the models were run for 24 hours.

The diffusion coefficients were calculated using *Sigmund* correlation [21]. This correlation is applicable to both oil and gas phases. The diffusion coefficient for propane calculated by the *Sigmund* correlation was in the order of 10^{-11} m²/s for the oil phase and 10^{-9} m²/s for the gas phase.

RESULTS AND DISCUSSION

The operating conditions and solvent system described in the previous section were applied to the model. The injection rate of solvent was set to 96 (cc/hr), which was injected continuously for 4 days into the model.

Fig. 9 shows the average pressure in each model in the first 24 hours. According to this figure, there was a small pressure rise at early times; each model approached

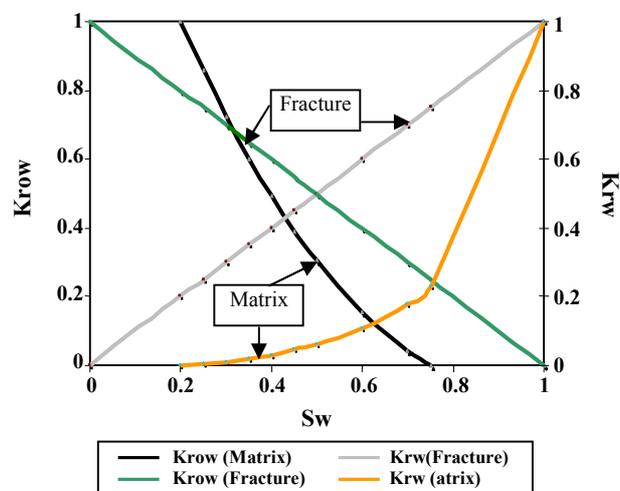


Fig. 8: Water-oil relative permeability curves for the Matrix and Fracture.

a uniform pressure after initial disturbances. However, the amplitude of initial surges in pressure became less as the fracture network distributed more extensively throughout the system and fracture spacing became smaller. The highest pressure rise occurred in the model with 1 matrix block, which was only 3.3 % higher than reservoir pressure. The least pressure disturbance at initial times occurred for the model with 49 blocks. This is due to the fact that the network of connected highly permeable channels, of fractures allows the solvent to rapidly distribute throughout the system, thus damping the pressure buildup that would otherwise occur in the system.

As the solvent flows through the fracture network, it bypasses the matrix blocks and forms a primary front around each block, where the solvent “fingers” into heavy oil reservoir and surrounds heavy oil matrix blocks. As a result, farther parts of reservoir are “touched” and affected by solvent stream and the oil inside the matrix blocks are surrounded by a solvent bank. Later, the oil zone in each block shrinks and the primary fronts combine to form secondary front which is similar to the dome-shaped front in conventional, non-fractured model [22].

The cumulative volumes of oil produced by each model after 24 hours are compared in Fig. 10. Also, the average oil production rate versus fracture spacing is shown in Fig. 11. According to these figures, the models with 9 and 25 blocks produced relatively equal volumes of oil. On the other hand, the model with 49 blocks gave

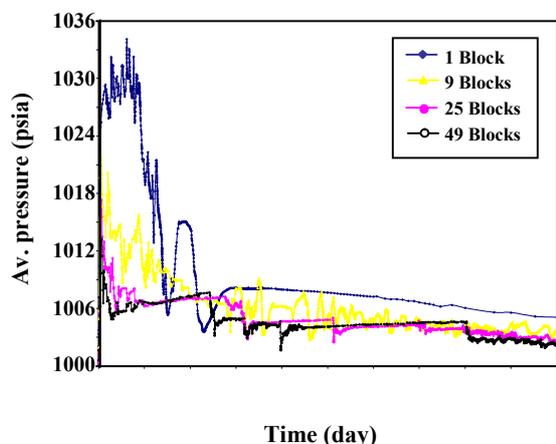


Fig. 9: Comparison of the pressure distribution in the models for 24 hours

the highest oil production rate in the same time and with the same solvent pore volume injection. Therefore, this model gives the highest cumulative volume of oil produced for the period of 24 hours.

The cumulative volume of gas produced in each model is shown in Fig. 12. It is clear from this figure that the cumulative gas production decreased when the number of matrix blocks increased from model with 1 block to model with 25 blocks. However, the model having 49 blocks produced much more gas in comparison with that with 25 blocks. Thus, higher oil production can be synchronous with greater gas production. However, the produced gas consisted mainly of non-condensable gas, and only small part of the solvent was produced as gas stream (Fig. 13). Fig. 13 shows the onset of gas breakthrough and the composition of gas that is produced through these models. According to this figure, the gas breakthrough in model 1 started after 0.1 days, whereas this occurred after 0.2, 0.3, and 0.5 days for models 2, 3 and 4, respectively. For comparison, the composition of injection gas is also shown in the same figure. The produced gas stream contained only 2.4 mol % of propane, whereas the injected solvent contained 25 mol % of propane. Comparing the composition of injected and produced gas streams showed that the produced gas contained essentially methane, the carrier gas, and little amount of propane. This is common in all models, which proves that most of the injected propane (main solvent) has been effectively diffused into heavy oil contained in the matrix. The composition of gas at the producer and the delay in the onset of gas breakthrough from system

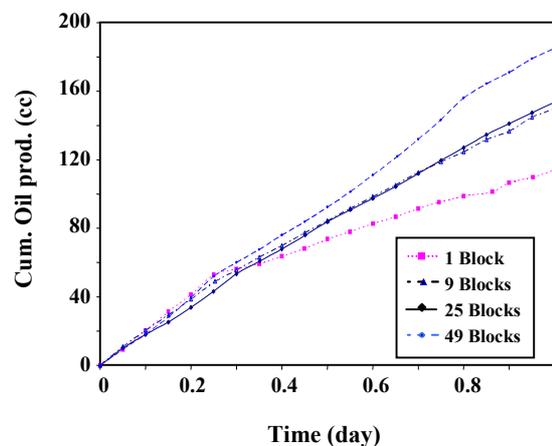


Fig. 10: Comparison of the Cumulative Oil production in the models for 24 hours.

are indications of the effectiveness of the VAPEX process containing extensive fracture network with close fracture spacing. The fracture network reduces the instabilities in the system pressure and damps pressure surges in the system by directing the injected solvent vapour towards highly permeable openings (or fractures). As a result, solvent-heavy oil contact area increases, which improves solvent diffusion into heavy oil. In addition, the solvent traverse between fracture network, rather than rapid flow towards the producer, delays the onset of solvent breakthrough and provides more residence time for the solvent to be in contact with heavy oil. Therefore, provided there is no significant thief zone, and fractures don't have connection to the surface, the concern about possible early solvent breakthrough is highly resolved. The contribution of fracture network in improved oil production is especially important when the VAPEX process is applied to low-permeability reservoirs.

WELL LOCATION AND SPACING

In VAPEX process, the injection and production wells are normally considered close to each other. This is because the VAPEX process is applied to heavy oil reservoirs where it is necessary to mobilize the highly viscous oil by dissolving solvent, so that it's ready to produce. If the wells are located far from each other, heavy oil needs to be produced by displacement, which is not easily feasible in heavy and extra-heavy oil reservoirs. On the other hand, if the wells are located too close to each other, there is a risk of early solvent breakthrough without efficient contact with heavy oil.

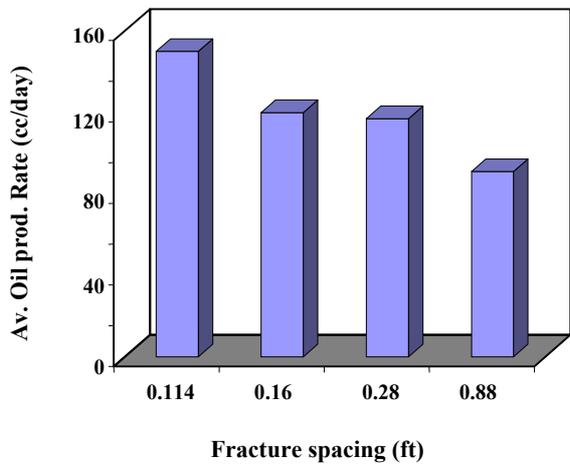


Fig. 11: Average oil production rate versus fracture Spacing.

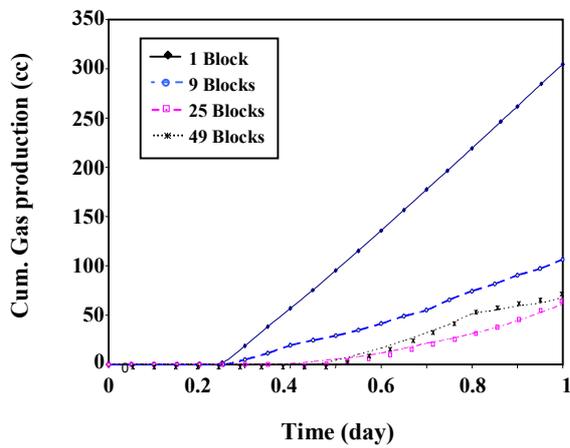


Fig. 12: Comparison of the cumulative gas production in the models for 24 hours.

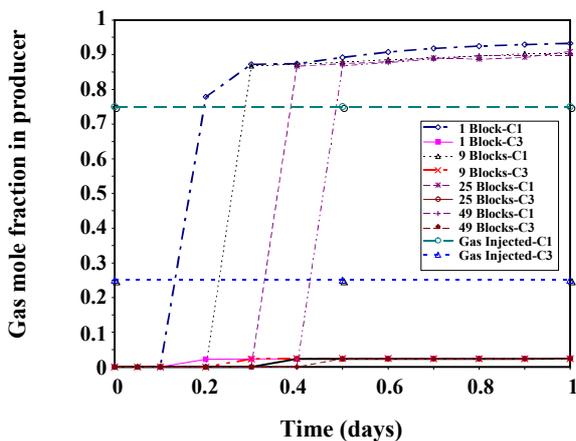


Fig. 13: Comparison of the composition of gas produced in the models for 24 hours.

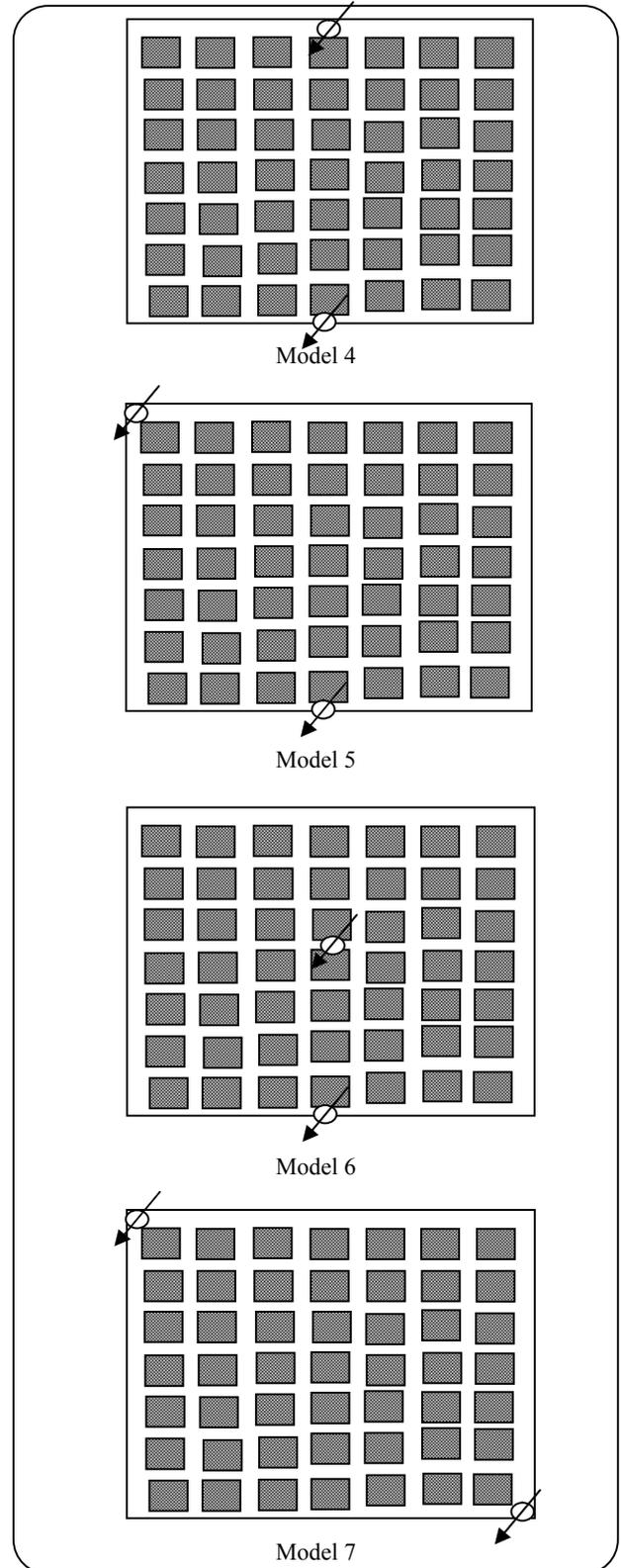


Fig. 14: Four different models used to study the effect of well spacing and location on the performance of the VAPEX process.

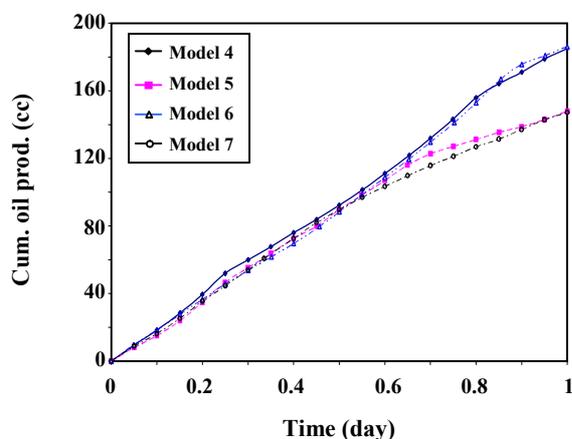


Fig. 15: Cumulative oil production in models 4-7 after 24 hours.

This is more important in the case of fractured reservoirs, as there is a risk of shortcut between injection and production wells through fracture network.

In order to study the effect of well location on process performance, the model with 49 matrix blocks described earlier (model 4) was regarded as the base case and the locations of wells were changed in three models shown in Fig. 14. In models 5 and 7, the wells are located as staggered pattern. The largest space between injector and producer is in model 7, where the injector and the producer are located at the top-left and bottom-right ends of the model, respectively. Also, in model 6, the injector is located at the middle, and has the least well spacing. The well spacing in models 4-7 is 0.837, 0.937, 0.476, and 1.185 ft, respectively. All other rock and fluid properties in the models were the same.

Fig. 15 compares the cumulative oil produced after 24 hours from these models. According to this figure, the oil production decreased with increase in the well spacing. When the injection and production wells were far from each other, the oil production was governed by displacement for quite a long time rather than the gravity drainage enhanced by the VAPEX process. This resulted in a decrease in heavy oil recovery.

The cumulative gas production by models 4-7 are compared in Fig. 16. According to this figure, when the injection and production wells were considered closer to each other, the onset of gas breakthrough started earlier. The highest volume of gas was produced in the model with the least well spacing. The high gas production in model 6 is attributed to a shortcut between injector and

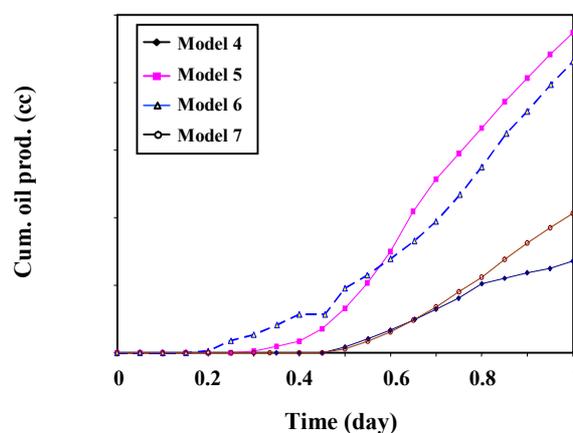


Fig. 16: Comparison of the cumulative gas production in the models for 24 hours.

producer through the fracture network. On the other hand, in model 4, the proper location of the injection and production wells resulted in a delay in gas breakthrough and solvent traverse between fracture network, rather than rapid flow towards the producer. Therefore, the well location is a critical issue when applying the VAPEX process in fractured systems.

CONCLUSIONS

In this work, the VAPEX process is studied using a compositional simulator on a number of single-block and multiple block fractured systems. PVT data of one of Iranian heavy oil reservoirs are used to tune the equation of state. Effects of fracture spacing on the performance of process were studied. It was found that:

- 1- Fracture network enhances the VAPEX process by improving the contact between solvent and oil contained in the matrix blocks.
- 2- The fracture network reduces the instabilities in the system pressure and damps pressure surges in the system during the VAPEX process.
- 3- The solvent traverse between fracture network delays the onset of solvent breakthrough and provides more residence time for the solvent to be in contact with heavy oil.
- 4- Under controlled conditions, existence of fracture network in low-permeability systems contributes and improves heavy oil production by VAPEX process.
- 5- The well location is a critical issue when applying the VAPEX process in fractured systems and affects the oil and gas production.

Abbreviations

API	American Petroleum Institute
CMG	Computer Modeling Group
CPU	Central Processing Unit
EOR	Enhanced Oil Recovery
SAGD	Steam-Assisted Gravity Drainage
VAPEX	Vapor Extraction

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