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Studying Pressure Variation in a Fractured Carbonate Reservoir Producing Under Steam Flooding EOR with Multiple Fracture Matrix Arrangements

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Abstract

The viscous oil reserves present around the world are estimated to be 2 trillion barrels, but to date, the lack of suitable technology for production causes these reserves present in complex reservoirs to negligibly contribute to world daily production. Most of these fractured reservoirs possess enormous heterogeneity due to high contrast between petrophysical parameters like porosity and permeability. Evaluating both the matrix and fractures is crucial for understanding these complex types of reservoirs. In oil and gas reservoirs, pressure is vital for maintaining the flow of hydrocarbons. Reservoir pressure helps push oil and gas through porous rock formations to production wells. The same pressure variation becomes very important during steam injection for recovering heavy oil from fractured carbonate reservoir. This study aims to capture pressure variation in different matrix-fracture arrangements. COMSOL Multiphysics® is used in this study, to map the pressure variation in a fractured carbonate reservoir producing under the steam flooding Enhanced Oil Recovery (EOR) technique. The results presented in this study reveal distinct pressure profiles for various fracture arrangements, including single horizontal & vertical fractures, closed loop arrangements, open loop arrangements, and irregular fracture networks. In a closed loop arrangement of matrix & fracture, pressure variations and compartmentalization effects are observed, necessitating precise management strategies to address isolated pressure responses. However, in an open loop arrangement, there are early pressure disturbances with dense fractures and delayed responses with wider fracture spacing, highlighting the influence of fracture density and spacing on fluid flow efficiency. This research contributes valuable insight for improved reservoir management.

Keywords:
fractured reservoir; pressure; matrix-fracture; carbonate

1. Introduction

Carbonate rocks are formed in a special environment and they are of biochemical origin. The complexity in a carbonate reservoir arises because of the post lithification process that induces secondary porosity, causing the formation of fractures which are distributed throughout the reservoir in a connected or disconnected network. These reservoirs contain around one fifth of the viscous oil resource. According to World Energy Outlook, by 2030, the energy demand could rise by 53% as a result of which the petroleum industry has to tackle the challenges faced in producing oil from fractured carbonate reservoirs.

Approximately 2 trillion barrels of heavy crude oil are present in heterogenous carbonate reservoirs, however it negligibly contributes to the world's oil production. These classes of reservoirs portray dual petrophysical properties, i.e. the presence of low permeable matrix and high permeable fracture, hence these reservoirs can be termed as complex and heterogenous in terms of petrophysical parameters. The recovery of heavy oil from Fractured Carbonate Reservoir (FCR) can only be accomplished by the use of thermal enhanced oil recovery technique. A fractured oil reservoir is characterized by presence of matrix and fracture sub-domains (**Tafti et al., 2021**). The matrix sub-domain has high storage capacity for crude oil, however the productivity of oil stored in it is much lower. On the other hand, fracture sub-domain has less storage capacity but high productivity. In addition, fractures don't generally direct liquid; they can act as a hindrance under certain conditions. A classification was suggested by (**Nelson, 2001**) for fractured domains, as shown in **Figure 1**,

- **i) Type I Reservoir:** reservoirs falling under this group have both porosity and permeability provided by a fracture sub-domain.
- **ii) Type II Reservoir:** these reservoirs have a low porosity & permeability matrix, & fractures pro-

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vide essential permeability for productivity. In this study, this reservoir is taken into consideration.

iii) **Type III Reservoir:** high porosity and they don't depend on fractures for getting the required production.

iv) **Type IV Reservoir:** reservoirs have a high matrix porosity and permeability, so open fractures can enhance permeability, but natural fractures often complicate fluid flow in these reservoirs.

Another reservoir class, Type G, has been created for unconventional fractured gas reservoirs, such as coalbed methane reservoirs, and fractured gas condensate reservoirs. Most Type G reservoirs fall within or near the Type II reservoir classification.

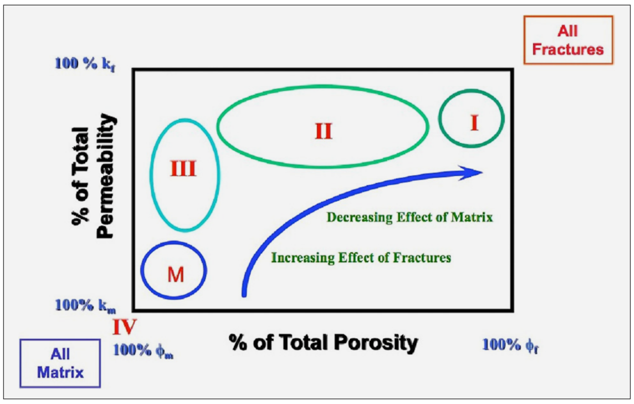

Figure 1: Classification of fractured reservoir (from **Nelson 2001**)

In this study, a Type II reservoir is considered where most of the hydrocarbon is stored in the matrix and the fracture helps in attaining the flow of fluids in the reservoir. Sandstone reservoirs can be mathematically modelled by assuming a single continuum (**Ansari & Govindarajan, 2023**) but FCRs possess low porosity, hence a lower thermal efficiency is expected. The complex interplay between fractures and matrix in these reservoirs significantly influences pressure variations and overall recovery efficiency (**Shiri & Shiri, 2021a**). Fractured carbonate reservoirs are characterized by their heterogeneous nature, where natural fractures significantly influence fluid flow and pressure distribution (**Shiri & Hassani, 2021**). The presence of fractures can either enhance or hinder the effectiveness of EOR techniques, depending on their distribution, orientation, and connectivity with the surrounding matrix. As a result, accurate prediction and management of pressure variations in these reservoirs become essential for designing effective steam flooding strategies. Steam flooding, which involves injecting steam to reduce the viscosity of heavy oil, introduces additional complexity into the pressure dynamics of fractured carbonate reservoirs. The steam injection alters the pressure distribution, potentially leading to uneven steam front advancement and varying degrees of pressure drop across the reservoir.

Fractures in carbonate reservoirs significantly affect fluid flow and pressure distribution (**Shiri & Shiri, 2021b**). Analysing the effects of fracture spacing and orientation on steam flood performance, **Zhao et al. (2019)** concluded that optimal fracture arrangements can reduce pressure fluctuations and improve overall recovery. The presence of natural fractures alters pressure distribution and fluid flow paths in a fractured carbonate reservoir (**Hadi et al., 2020**). Optimal fracture spacing and orientation are crucial for effective steam flooding. The investigation on the effects of fracture spacing and orientation on pressure variation and steam distribution is of utmost importance, as these factors significantly influence EOR performance (**Wu et al., 2020**). Experimental data from laboratory and field studies validate numerical models and provide empirical evidence of pressure variations. The field trials in fractured carbonate reservoirs confirm the predictions of numerical simulations regarding pressure dynamics during steam flooding (**Patel et al., 2021**). The spacing and orientation of fractures are critical for steam distribution and pressure management. Pressure variations during steam flooding are a key consideration. Steam injection rates and fracture characteristics significantly affect pressure profiles. Their study uses field data and simulations to analyse these effects (**Lee et al., 2022**).

Albeit the recent advancements in numerical modelling and simulation have provided valuable insight in deducing the spatial and temporal distribution of pressure variations in fractured reservoirs, the sensitivity of the fracture network concept (which closely reflects the reality) in steam-flooding applications that dictates the resulting pressure distribution in a fractured reservoir against the application of the conventional regular single fracture-matrix system remains unexplored. Addressing this gap remains to be vital for improving the predictive accuracy of reservoir performance and enhancing the overall efficacy of steam flooding EOR. This research aims to investigate the effects of various fracture-matrix arrangements under the umbrella of a fracture network concept that closely reflects the reality on pressure variation in fractured carbonate reservoirs undergoing steam flooding. This study seeks to elucidate the relationship between fracture characteristics and pressure dynamics during steam injection. The findings are expected to contribute to the development of optimized steam flooding strategies, ultimately leading to more efficient hydrocarbon recovery from fractured carbonate reservoirs. This paper addresses a critical aspect of EOR in fractured carbonate reservoirs, focusing on the interplay between fracture-matrix arrangements and pressure variation. The insight gained from this research will provide a deeper understanding of the factors influencing steam flooding performance and offer practical guidance for enhancing EOR techniques in complex reservoir systems. The findings are anticipated to provide valuable insight for reservoir engineers and contribute to the de-

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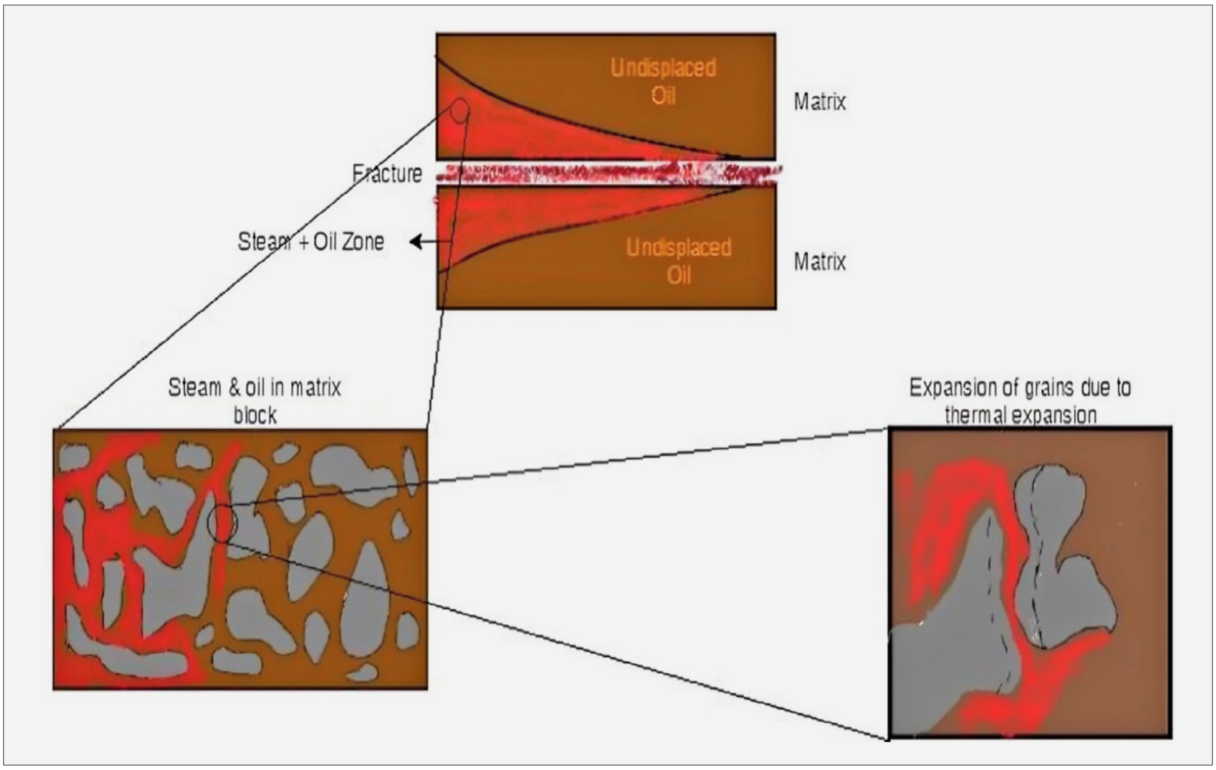

Figure 2: A scheme depicting the effect of injection of steam in a matrix with a single horizontal fracture arrangement

velopment of optimized EOR strategies that can enhance the recovery efficiency of fractured carbonate reservoirs producing under the steam flooding EOR process.

2. Conceptual model

In fractured carbonate reservoirs, pressure variation is influenced by the complex interaction between fractures and the surrounding rock matrix. Fractures typically have much higher permeability than the matrix, leading to uneven pressure distributions. This disparity can cause rapid pressure changes within fractures while the matrix experiences more gradual adjustments. During extraction or injection processes, pressure transients travel swiftly through fractures, often resulting in pronounced pressure fluctuations. The efficiency of pressure maintenance strategies, such as water or gas injection, hinges on the ability to balance pressure between fractures and the matrix to ensure optimal reservoir performance and stability.

Flow Mechanism in a Fractured Reservoir:

- **Matrix Flow**: typically occurs through the porous matrix and is generally slower due to lower permeability.
- **Fracture Flow**: occurs through fractures and can be much faster due to higher permeability.

As far as steam flooding is concerned, injecting steam increases the pressure within the reservoir, reduces oil viscosity, improves mobility ratio, reduces interfacial tension, and increases the relative permeability of oil. This pressure boost helps push the heated oil towards production wells. The pressure and temperature changes can also affect the rock matrix and fractures, influencing oil mobility. Steam flooding with matrix fracture networks highlights how the effectiveness of steam flooding in Enhanced Oil Recovery (EOR) is significantly influenced by the presence and characteristics of matrix fractures within the reservoir, as shown in **Figure 2**. Fractures in the rock matrix act as a pathway of higher permeability compared to the surrounding rock. This enhanced permeability allows the steam to penetrate deeper and more effectively into the reservoir. Consequently, the steam reaches a larger volume of oil, improving the overall efficiency of the flooding process. In contrast, this can also be a reason attributing to steam breakthrough in which steam is injected into a reservoir for enhanced oil recovery, and unexpectedly reaches the production wells before it has fully traversed the intended area of the reservoir. This phenomenon can lead to premature and less efficient recovery of oil.

3. Matrix-Fracture arrangements

The main motive of this study is to map the pressure variation in a fractured carbonate reservoir and for the same to analyze the pressure change in the geometry for different matrix and fracture arrangements. This will help in comprehensively understanding the role of fractures in pressure transport and its effect on heavy oil production in the reservoir.

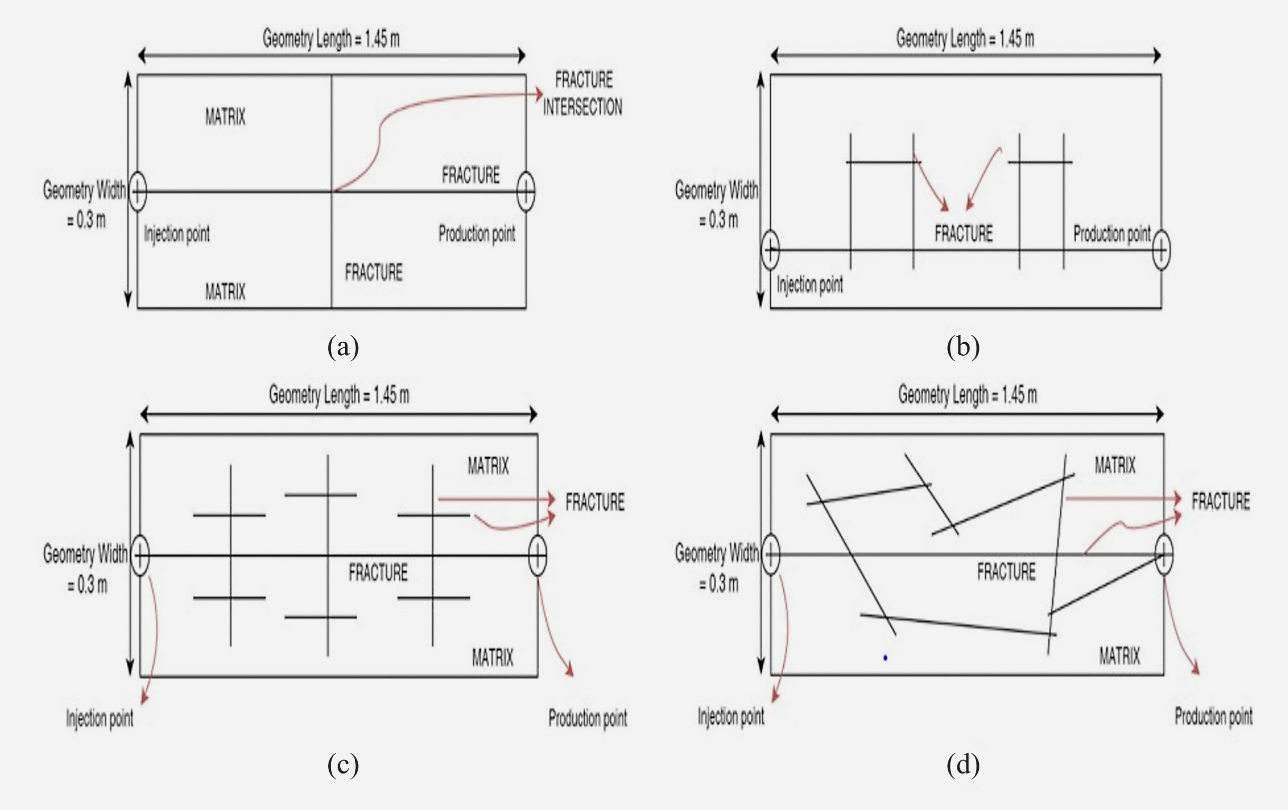

Figure 3: a) Schematic of single horizontal and vertical fracture, b) closed loop arrangements, c) open loop arrangement, d) irregular fracture networks.

A simple fracture matrix arrangement is considered, as shown in **Figure 3a**. In this geometry, one horizontal and one vertical fracture is accompanied with matrix subdomain. In this geometry, two sets of points are considered namely injection and production points respectively.

Following this arrangement, a number of arrangements are tried to study pressure variation for different matrix and fracture combinations. The main reason behind this is to make fracture and matrix combinations in the reservoir more complex, so that such a reservoir model can be obtained which can be closer to the real scenario. The arrangement in **Figure 3a** has two fractures (horizontal and vertical) within the matrix (**Kharrat et al., 2023**). This arrangement has been chosen in the study to address the importance of vertical fractures in pressure variations inside the reservoir along with a horizontal fracture.

The geometry depicted in **Figure 3b** contains such a combination of fracture and matrix which can be called a closed loop arrangement of matrix and fracture, in which a unique arrangement in terms of fracture and matrix is taken into account. The small fractures in the matrix are considered as an embedded fracture and its effect on pressure change is studied in this paper. Two closed loop fracture matrix combinations are obtained in this geometry, in order to study the pressure variations inside the closed loop and also near its vicinity. Understanding the distribution and characteristics of fractures, as shown in **Figure 3b**, is important for designing effective injection and extraction strategies. For example, in enhanced oil recovery (EOR) processes, knowing the fracture network helps in planning the injection of fluids like steam to maximize recovery. Fractures influence the pressure distribution within the reservoir. Properly accounting for fractures in reservoir models helps in managing reservoir pressure and optimizing production (**Nitao et al., 2015**).

Along with all these geometries, an open end with varying spacing of fracture in a fracture-matrix arrangement is considered, as shown in **Figure 3c**. The open-loop fracture-matrix arrangement helps to study how different factors (such as fracture spacing) influence the overall fluid flow and recovery efficiency. In an open loop arrangement, fractures are embedded in the matrix in such a way that they don't form a sub matrix. The fractures shown in **Figure 3d** are not parallel or uniformly spaced, and they intersect at various angles, creating a complex network for fluid flow. Fluid flow pressure contours will not be evenly distributed, with some regions experiencing higher pressure due to better connectivity through the fractures, while other regions might have slower fluid movement. This arrangement reflects the natural heterogeneity often found in geological formations. Real-world reservoirs rarely have uniform fracture networks, so understanding and modelling these irregularities is crucial for accurate predictions of fluid behaviour.

4. Mathematical model

For obtaining the flow equations, the mass balance and Darcy's equation is combined to give a continuity equation, for the two phases (oil and steam) considered in a 2-dimensional flow taken into account in this model (**Jensen et al., 1992**). Following a partial differential equation was defined in COMSOL Multiphysics® along with the fracture matrix arrangements to solve the pressure variation for different matrix and fracture arrangements:

Oil Phase:

$$\varnothing \rho_o \frac{\partial (S_o)}{\partial t} = \frac{k_x}{\mu_o}\frac{\partial}{\partial x}\left[k_{ro}\rho_o \frac{\partial}{\partial x}(P_o - \rho_o gH)\right] + \frac{k_z}{\mu_o}\frac{\partial}{\partial z}\left[k_{ro}\rho_o \frac{\partial}{\partial z}(P_o - \rho_o gH)\right] + q_o \quad (1)$$

Steam Phase:

$$\varnothing \rho_s \frac{\partial (S_s)}{\partial t} = \frac{k_x}{\mu_s}\frac{\partial}{\partial x}\left[k_{rs}\rho_s \frac{\partial}{\partial x}(P_s - \rho_s gH)\right] + \frac{k_z}{\mu_s}\frac{\partial}{\partial z}\left[k_{rs}\rho_s \frac{\partial}{\partial z}(P_s - \rho_s gH)\right] + q_s \quad (2)$$

Auxiliary Equations:

$$\sum S_i = 1.0, i = o \,\&\, s \quad (3)$$

$$P_s - P_o = P_{cso}(S_s) \quad (4)$$

Where, P is the pressure in psi, ρ is density in g/cm^3, Ø is porosity, k is permeability in darcy/milli darcy, k_r is relative permeability, x is distance in x direction, z is distance in y direction, and S is saturation.

The left side of the equation describes the temporal change in oil saturation within the reservoir, factoring in the reservoir's porosity and the density of the oil. The right side of the equation consists of two terms that capture the pressure distribution in the reservoir. These terms are derived from Darcy's Law, adjusted for the relative permeability and gravity effects. These terms describe the pressure gradient in the reservoir. They account for the variations in pressure due to changes in both the x and z directions, incorporating the relative permeability of the oil and the influence of gravity (through the term ρgH). The source term adds flexibility to model additional complexities such as fluid injection or extraction processes. The following assumptions hold valid for this case: i) isothermal conditions (constant temperature), ii) Darcy's law is valid for describing fluid flow, iii) no chemical reactions between the phases, iv) the porous medium is homogeneous and isotropic.

These equations model the dynamics of two-phase flow (oil and steam) in a porous reservoir. The pressure distribution and fluid flow are governed by the balance of forces, including viscous, gravitational, and capillary forces. The oil and steam phases interact through relative permeabilities and capillary pressures, which are functions of saturation. The following steps were followed for setting up a model in COMSOL Multiphysics ®:

i) defining the spatial domain of the reservoir for all four fracture-matrix arrangements,
ii) used custom equations, in the "Coefficient Form PDE" or "General Form PDE" interface to input the governing equations. Implemented the capillary pressure equation as an auxiliary equation or using a variable expression,
iii) used Subsurface Flow Module for handling two-phase flow (e.g. oil and steam),
iv) defined all the material properties, porosity, permeability, density, etc. into the model,
v) applied initial and final boundary conditions. No flow boundary condition is set in this model.

5. Results and discussion

The verification and validation of the results were done by numerical results and experimental results given by **Jensen et al. (1992)**. The simulation was run for a core having a length of 30.39 cm and a height of 5.04 cm. The simulation studies were carried out in COM-

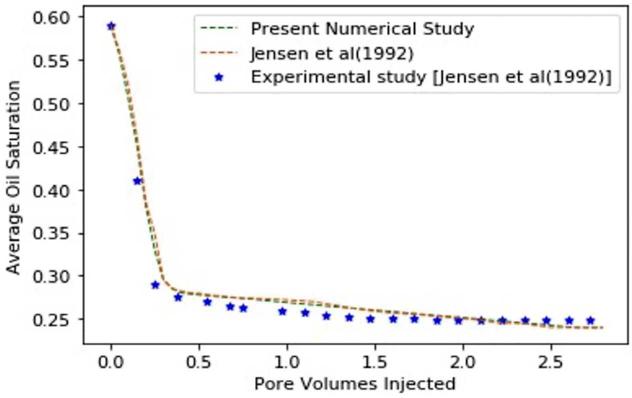

Figure 4: Verification and validation plot for steam flooding in an FCR (**Jensen et al., 1992**)

Table 1: Input value for simulating the reservoir

Variable	Value	Variable	Value
Length (m)	1.45	Fracture Permeability (D)	100
Height (m)	0.3	Fracture Aperture (cm)	0.025
Matrix Porosity	0.186	Oil Density (kg/m^3)	897
Fracture Porosity	1.0	Steam Density (kg/m^3)	1000
Matrix Permeability (mD)	100	Inlet Pressure (psi)	3000

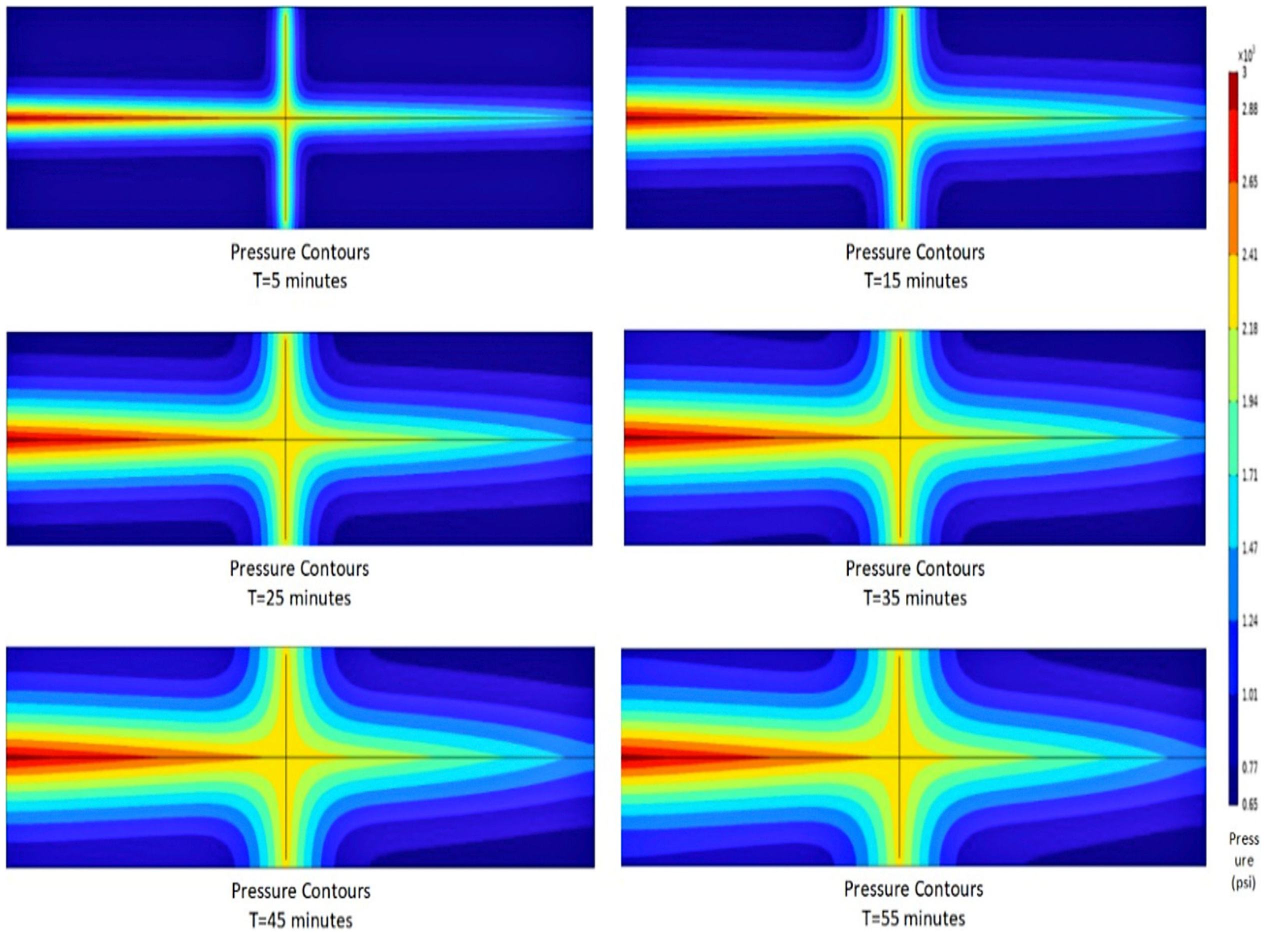

Figure 5: Schematic showing pressure contours for a single horizontal and vertical fracture case (benchmark) at T=5, 15, 25, 35, 45 and 55 minutes

SOL Multiphysics which is a finite element analysis-based simulation tool. The matrix permeability taken for validation and verification purposes is 100 mD. The matrix porosity, fracture porosity and fracture permeability were taken as 0.186, 1 and 100 D respectively. The numerical results obtained from COMSOL Multiphysics showed a reasonable and good fit with the experimental and numerical results presented by Jensen et al. (1992) (see **Figure 4**).

The plot depicts a decrease in heavy oil saturation when steam is injected inside the core sample, which is very evident from a conventional core flooding experiment. Along similar lines, an attempt has been done in this study to examine pressure variation inside an FCR producing under steam flooding EOR with changing matrix and fracture arrangements.

A hypothetical reservoir was considered to carry out the simulation at a larger scale, so that analyses of pressure changes can be done and accordingly efficient reservoir optimization can be performed at a larger scale. No flow boundary condition is imposed on all matrix boundaries and an inlet pressure and outlet pressure of 3000 psi and 1000 psi is assigned for matrix subdomain.

Figure 5 depicts the pressure contour profile for a reservoir having a single horizontal and vertical fracture present. The pressure near the injection point is higher and it continues decreasing towards the production point.

The pressure profile observed in the arrangements shown in **Figure 5** can be divided into four parts, namely: i) injection pressure profile at start of injection, ii) increase in pressure in fracture, iii) pressure distribution in matrix and iv) pressure stabilization.

In part 1, i.e. **T = 5 minutes**, the pressure in the reservoir increases as the injected fluid starts to enter the fractures and parts of the matrix close to the injection point. The initial pressure required to start injection depends on the reservoir's capillary pressure and the entry pressure of the fractures. It is very interesting to note that more inter-porosity flow (from fracture to matrix) will take place near the vicinity of the injection point. In part 2, i.e. **T = 15 minutes**, fractures will experience a rapid increase in pressure. The pressure in fractures rises relatively quickly as the injected fluid moves through them. Inter-porosity flow and the presence of vertical and horizontal fractures are key factors influencing fluid dynamics in subsurface reservoirs. They are generally less common but can still have a significant impact on fluid

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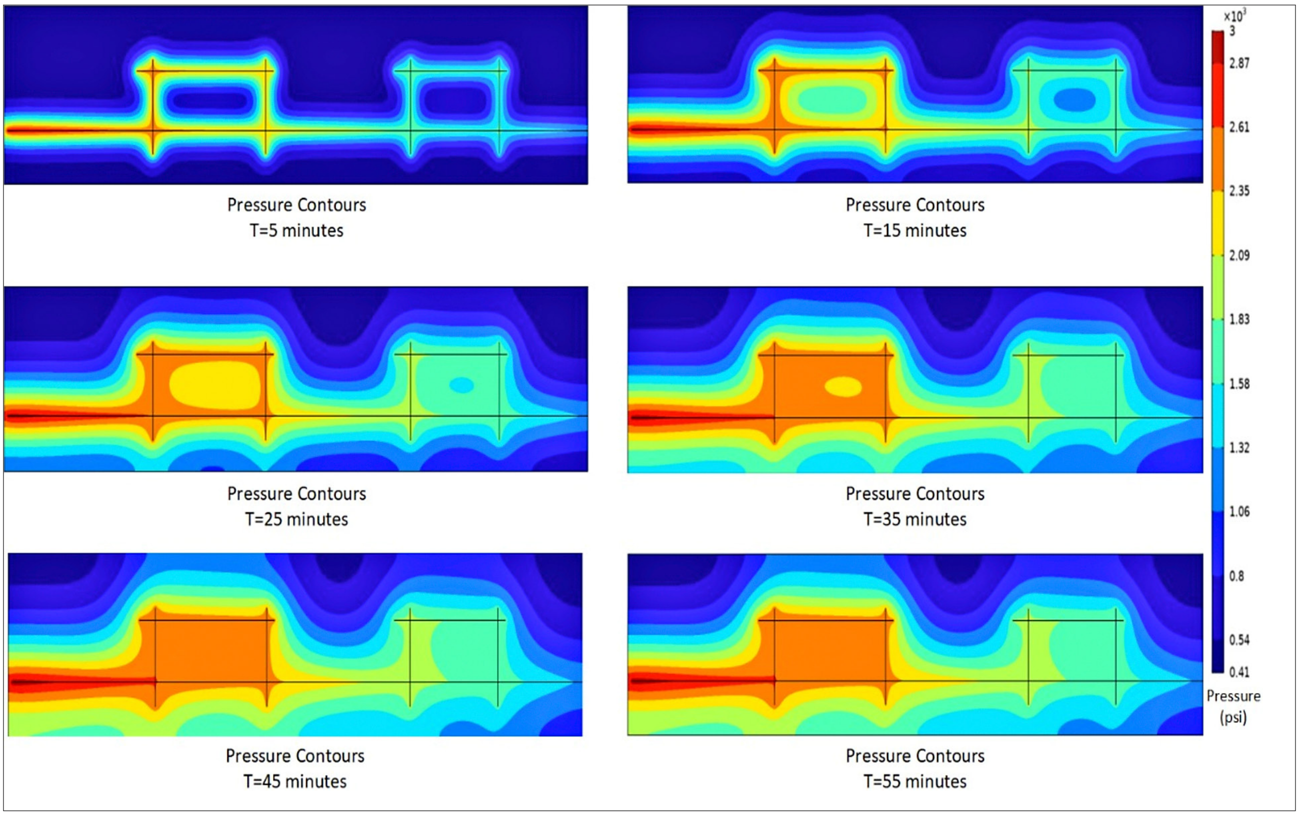

Figure 6: Schematic showing pressure contours for closed loop embedded fracture arrangement at T = 5, 15, 25, 35, 45 and 55 minutes

flow. Since both of the fractures are considered conductive in this case, it is evident that they enhance the inter porosity flow. In part 3, the matrix, being less permeable, will exhibit a slower increase in pressure. Fluid injected into the matrix will create a pressure front that gradually propagates from the fracture-matrix interface into the matrix. In part 4, after the initial surge, the pressure in the fractures tends to stabilize as the fluid injection continues. The pressure in the matrix, however, continues to rise more slowly as the pressure front advances. Also, after examining the pressure profiles, it is seen that steam breakthrough can occur when steam injected into a fractured reservoir reaches production wells earlier than expected due to the high density of a fracture embedded in the matrix. This may lead to reduced steam efficiency due to a reduction in the time steam has to effectively heat the reservoir and mobilize the oil, leading to less effective thermal recovery.

In a real reservoir case, there may be instances where the intersection of fractures can cause the formation of a sub-matrix domain surrounded by fractures within the primary matrix (**Smith, J., & Jones, A. 2020**). In this study, a practical case is represented and pressure variation in such complex geometry is simulated, as shown in **Figure 6**.

It is observed that the pressure intensifies in the sub-matrix domain due to the aid provided by a fracture around its surroundings. It is also very important to note that pressure variation inside the sub-matrix domain causes a huge pressure variation in the nearby primary matrix formation. Due to the presence of a greater number of fractures per unit area, it can be seen that the fracture presence causes the pressure to almost equalize within the sub-matrix and in the vicinity of the injection point. This scenario occurs due to the compartmentalization effect created by fractures, which can isolate parts of the reservoir and lead to pressure differentials, which can be seen in **T = 35 minutes, T = 45 minutes and T = 55 minutes**. A delayed pressure response is seen in the second local sub-matrix shown in **Figure 6**, due to a single fracture conducting the injection pressure to producers. This study will help in accurately placing the injectors.

An open loop fracture-matrix arrangement is also investigated in this study, as shown in **Figure 7**. In this case, it is observed that due to the presence of numerous fractures towards the injection point, the pressure disturbance gets transported very early, around 5 minutes after injection. In the middle, like in the fracture and matrix arrangement depicted in **Figure 7**, the distance between fractures is intentionally increased higher than in the surrounding arrangements to establish the fact that if the distance between fractures is higher, the pressure response is delayed. It is very much evident from results presented in **Figure 7**, that the distance between the fractures causes a delay in inter-porosity flow.

In addition, the presence of numerous fractures towards the injection point leads to the pressure distur-

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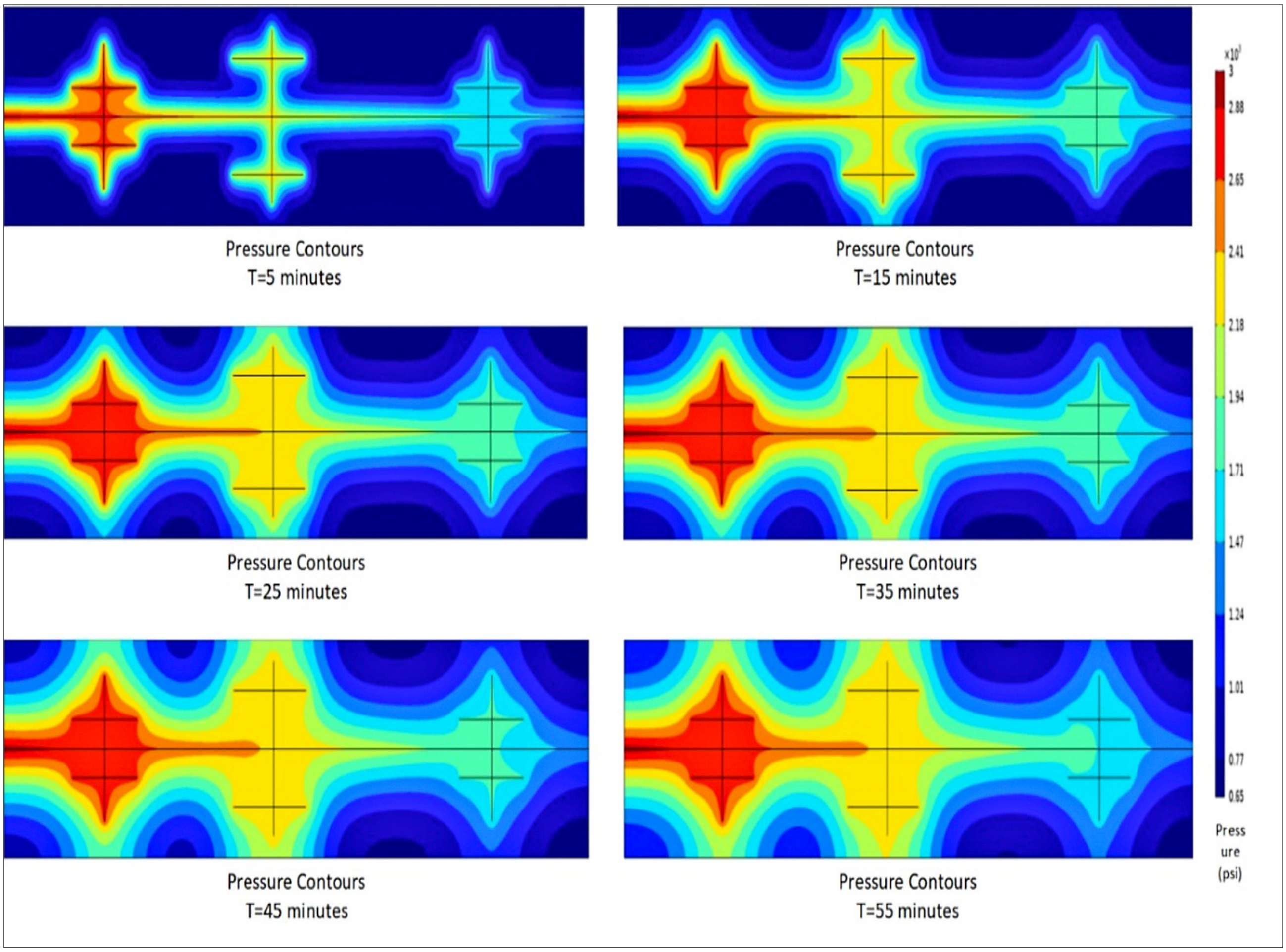

Figure 7: Schematic showing pressure contours for open loop embedded fracture arrangement at T = 5, 15, 25, 35, 45 and 55 minutes

bance being transported very early, around **T = 5 minutes** after injection. Wider spacing between fractures reduces connectivity, which can lead to isolated pressure compartments within the reservoir. Wider-spaced fractures result in more localized pressure changes, where pressure might be higher near the fractures and lower in the areas between them, as seen in the results of **T = 15 minutes**. In regions with sparse fractures, pressure drops are more pronounced as fluids have to travel longer distances through the less permeable matrix rock. As shown in **Figure 7**, pressure management poses a major challenge, as fluids might not distribute evenly, leading to inefficiencies in fluid recovery as depicted in the results of **T = 55 minutes**. To tackle this, targeted injection strategies can be opted to focus on areas with higher fracture density to improve pressure management and fluid distribution. Also, if the arrangement shown in **Figure 7** is upscaled to a bigger area of interest, regular monitoring reservoir pressure is mandatory to identify areas with significant pressure drops. This will help in adjusting steam injection rates and production rates to efficiently sweep the reservoir.

The pressure contour in an irregular matrix fracture arrangement is shown in **Figure 8**. In this geometric configuration, the upper limit of pressure values is transmitted extensively and at high frequency.

This is because of a higher number of fractures per unit area. If a production well is present in such a reservoir, then the injection pressure effect can be seen very early in the production well, hence chances of early steam breakthrough is evident. In reservoirs with irregular closed fractures, the steam injection must account for the complex geometry and connectivity of the fracture network. Irregular fractures can lead to uneven steam distribution as seen in **T = 15 minutes and T = 25 minutes**, affecting the efficiency of the process. In T=55 minutes, irregular fractures cause steam to bypass certain areas or create preferential pathways, which may lead to non-uniform heating of the reservoir. However, in this case, segmented or staged steam injection strategies are preferred to add less uneven steam distribution and improve overall recovery efficiency. Pressure variation shows that injection into high-permeability fractures dissipated too quickly, leading to uneven displacement. Hence, modified steam injection rates and patterns to balance pressure and improve matrix drainage is of the utmost importance in irregular fracture arrangements.

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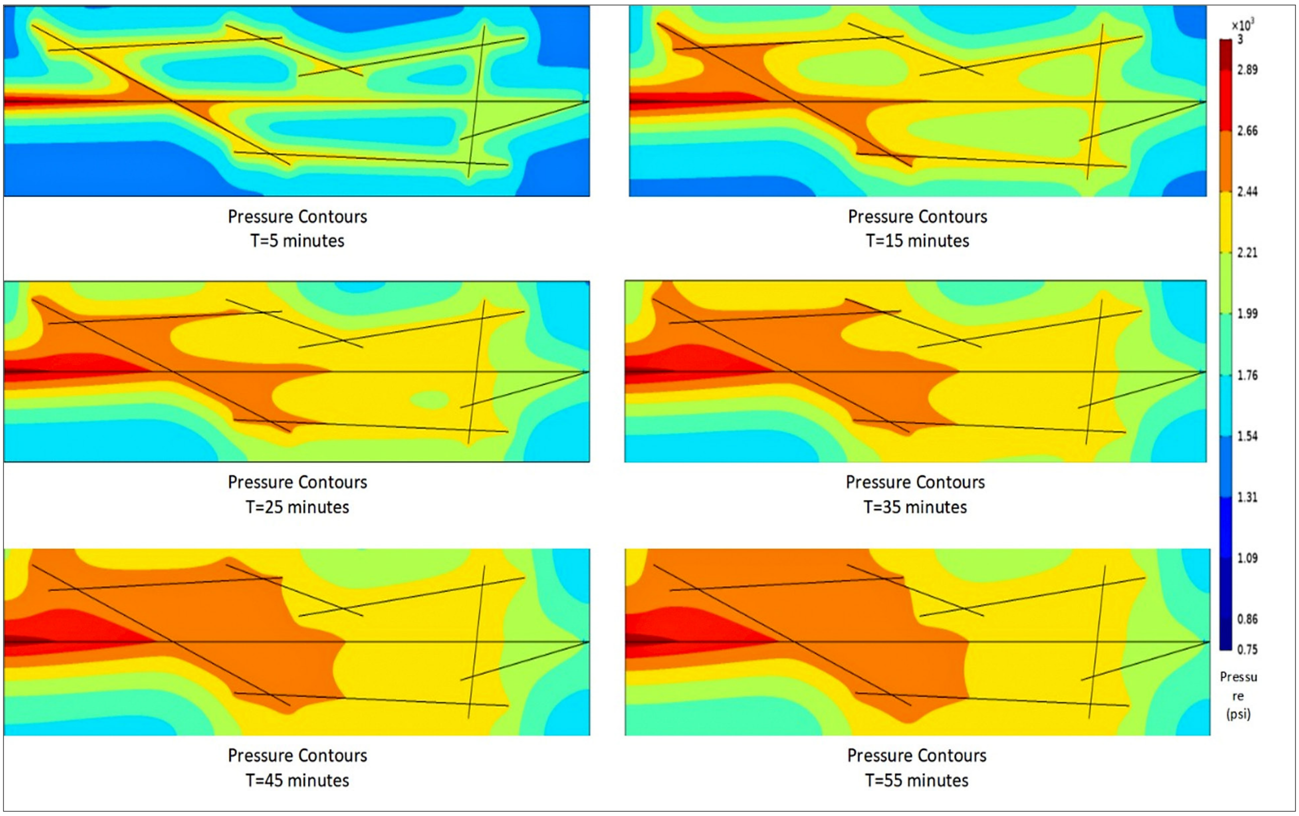

Figure 8: Schematic showing pressure contours for irregular closed fracture arrangement at T = 5, 15, 25, 35, 45 & 55 minutes

5. Conclusions

This study provides a comprehensive analysis of pressure variation in fractured reservoirs under steam flooding enhanced oil recovery (EOR) through numerical simulations and comparisons with experimental data. The findings, validated against the work of **Jensen et al. (1992)**, demonstrate that the COMSOL Multiphysics ® simulation tool effectively models the pressure dynamics in such reservoirs, showing a strong agreement with both experimental and numerical results. The results reveal distinct pressure profiles for different fracture configurations, emphasizing the impact of fracture arrangements on pressure distribution and fluid flow dynamics. The study highlights four key phases in pressure evolution: the initial pressure surge, rapid increase in pressure within fractures, gradual pressure rise in the matrix, and eventual pressure stabilization. These phases are crucial for understanding how steam flooding influences reservoir pressure and oil mobilization. From this study, it can be concluded that,

- In the case of a single horizontal and vertical fracture, pressure increases rapidly in the fractures and gradually in the surrounding matrix, leading to faster steam breakthrough and potential reduction in thermal recovery efficiency. Conversely, scenarios with multiple fractures or complex fracture networks, such as closed loop and irregular arrangements, introduce significant pressure variations and potential compartmentalization effects. These effects can lead to non-uniform pressure distribution and early steam breakthrough, necessitating targeted injection strategies and regular monitoring to optimize recovery.
- The results underscore the importance of considering fracture density and spatial arrangement in reservoir management. Fracture networks significantly influence pressure dynamics and fluid distribution, and an accurate understanding of these factors can enhance the efficiency of steam flooding operations.
- For practical applications, tailored injection strategies and regular pressure monitoring are recommended to address challenges posed by complex fracture geometries and optimize reservoir performance.
- In a closed loop fracture arrangement, the pressure tends to equalize within sub-matrix domains surrounded by fractures, causing complex pressure distributions that necessitate precise management strategies. The compartmentalization can isolate parts of the reservoir, leading to delayed pressure responses in certain areas.
- In an open loop fracture arrangement, increased fracture density near the injection point results in early pressure disturbances, while wider spacing between fractures causes delays in pressure responses. This underscores the importance of frac-

ture spacing in determining fluid flow efficiency and pressure management. Wider spacing can lead to localized pressure changes and reduced fluid recovery efficiency.

- In an irregular fracture network, there are extensive and frequent pressure variations. This can cause uneven steam distribution and potential steam bypassing in certain reservoir areas, which may impact overall recovery efficiency. The study suggests that segmented or staged steam injection strategies could be beneficial in such cases to address uneven steam distribution.
- In a real field case scenario, the pressure management discussed is crucial to ensuring fracture contribution to oil without bypassing matrix oil. This pressure variation study will help in making important field decisions to optimise recovery from such types of complex reservoirs.

This study provides a foundation for future research on fractured reservoirs under steam flooding. Future work should focus on further validating these findings with field data and exploring advanced simulation techniques to capture more complex reservoir behaviours. Additionally, investigating the impact of different steam injection rates and alternative EOR methods in various fracture configurations could provide deeper insight into optimizing recovery processes.

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SAŽETAK

Istraživanje promjena tlaka u raspucanome karbonatnom ležištu s različitim rasporedom višestruko frakturirane matrice iz koje se proizvodnja odvija uz primjenu povećanja iscrpka nafte utiskivanjem vodene pare

Globalne rezerve viskozne nafte procijenjene su na 2×10^{12} barela, no do danas, zbog nedostatka odgovarajuće tehnologije proizvodnje, te rezerve prisutne u složenim ležištima zanemarivo doprinose dnevnoj proizvodnji nafte. Većina tih raspucanih ležišta karakterizirana je izrazitom heterogenošću zbog velike razlike među petrofizičkim parametrima poput poroznosti i propusnosti. Za razumijevanje ovih složenih vrsta ležišta ključno je procijeniti i matricu i pukotine. U naftnim i plinskim ležištima za održavanje protoka ugljikovodika ključan je tlak. Tlak ležišta potiskuje naftu i plin kroz poroznu formaciju do proizvodne bušotine. Tijekom pridobivanja teške nafte iz frakturiranih karbonatnih ležišta utiskivanjem pare iznimnu važnost ima promjena tlaka. Cilj je ovoga istraživanja utvrditi različite promjene tlaka u različitim rasporedima matrice i pukotina. U ovome je istraživanju za praćenje i bilježenje promjena tlaka u raspucanome karbonatnom ležištu, iz kojeg se proizvodnja odvija uz primjenu tehnologije povećanja iscrpka nafte utiskivanjem pare, korišten računalni program COMSOL Multiphysics®. Rezultati istraživanja pokazuju različite profile tlaka za različite rasporede pukotina, uključujući pojedinačne horizontalne i vertikalne pukotine, raspored u obliku zatvorene i otvorene petlje i nepravilne mreže pukotina. U rasporedu matrice i pukotina u obliku zatvorene petlje uočeni su učinci promjene tlaka i kategorizacije, zbog čega su, kako bi se moglo riješiti pojedinačne promjene tlaka, potrebne precizne strategije upravljanja. S druge strane, u rasporedu u obliku otvorene petlje raniji poremećaji tlaka u slučaju gušćih pukotina i kašnjenje u odgovoru u slučaju većega razmaka među pukotinama ističu utjecaj gustoće pukotina i njihove međusobne udaljenosti na učinkovitost protjecanja fluida. Ovim istraživanjem dobiveni su vrijedni rezultati koji se mogu koristiti za poboljšanje razrade ležišta.

Ključne riječi:
raspucano ležište, tlak, matrica-pukotina, karbonati

Author's contribution

Shantanu Pandey (Research Scholar) – conceptualization, formal analysis and writing. **Suresh Kumar Govindarajan** (Full Professor) – conceptualization, formal analysis and manuscript final correction.