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A Comprehensive Study of Naturally Fractured Reservoirs Sensitizing the Importance of Grid Block Shapes and Fracture Capillary Pressure Existence on Fluid Flow Dynamics

*M.Haris, M.K. Zahoor, H. Jehanzaib, M.R. Latif, A.S.A. Shahid**

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Abstract

Carbonate or naturally fractured reservoirs have vast reserves of hydrocarbons that can help to fulfill energy needs. However, the modeling of these reservoirs is a challenging task due to several technicalities involved. These include matrix-fracture transfer rate and subsequent flow of fluid towards the wellbore. In order to investigate this particular and complex fluid flow mechanism, the grid block shape has been varied from typical cubical to elongated parallelopiped and slab type during numerical simulation studies. Further, the effects of fracture capillary pressure on reservoir performance have been investigated for these block types in the water injection process. This in-depth investigation, at a broader level of its kind, shows that with the increase in fracture capillary pressure as a function of matrix capillary pressure, there is a significant decrease in hydrocarbon recovery. Moreover, a drastic change in recovery has been observed by switching to slab and matchstick-type grid block shapes rather than simple cubical grid block shapes. The obtained results provide a new insight into the modeling of naturally fractured reservoirs and fluid flow dynamics, which can lead to improved hydrocarbon recovery estimations along with better designing of the water injection process.

Keywords: Hydrocarbon Recovery, Capillary Pressure, Grid Block Shape, Naturally Fractured Reservoir.

1. Introduction:

Naturally fractured reservoirs (NFRs) are considered the world's most enormous oil resources [1-3]. NFRs are complex, having a complicated matrix fracture system, which leads to different block shapes while conducting numerical simulation studies. Further, the existence of flow-affecting parameters in fracture networks, i.e., capillary pressure and relative permeability, and their role in fluid flow dynamics is still a myth [4].

NFRs studies can be found in the literature from the mid-1990s. Barenblatt et al. [5] made one of the earliest attempts to understand the fluid flow behavior in NFRs. Their outcomes were more elaborated by Warren and Root [6], who studied an idealized model of small matrix blocks with complex interconnected fractures while adopting the dual porosity single permeability concept (2ϕ, 1k), which states the restriction of fluid re-entry in matrix block. Later, the concept of dual porosity dual permeability model (2ϕ, 2k) was introduced by Blaskovich *et al*. [7], focusing on the contribution of matrix to matrix flow in NFR, as well.

Rock properties (such as porosity and permeability) play a significant role in fluid flow through NFR and tight sands. Macdonald *et al*. [8] analyzed the effects of pressure variations and relative permeabilities in the matrix and fracture. They concluded that

[1] *Department of Petroleum & Gas Engineering, University of Engineering & Technology Lahore, Pakistan*
Corresponding Author E-mail: arshad.shahid@uet.edu.pk

simulation studies should incorporate pressure effects for matrix and fracture parameters. Capillary pressure as a flow-effecting parameter can also affect the fluid dynamics within a reservoir. Researchers have emphasized the role of capillary pressure in achieving accuracy in recovery estimations [9-12]. The effects of capillary pressure existing between gas, oil, and water were analyzed under different recovery processes for both conventional and fractured reservoirs by Shams *et al.* [13]. They reported that capillary pressure does not have a vital role in flow calculations in every case; hence, they presented the guidelines when capillary pressure is important, but they did not incorporate the sensitivity of fracture capillary pressure variations.

Bander *et al.* [14] checked the effects of capillary pressure and relative permeability in gas condensate NFRs. They analyzed that a decline in pressure causes retrograde gases to convert into condensate, resulting in a reduction in recovery. They also showed that capillary pressure has no significant effect on recovery decline, while relative permeability changes with the change in the quantity of condensate. Noorozi *et al.* [15] investigated NFRs emphasizing the use of a dual porosity dual permeability model while incorporating fracture parameters, like matrix-fracture transferability, dimensionless fracture height, and fracture aperture. The sensitivity analyses for different production mechanisms were also made.

The fluid flow in NFR considerably depends on the shape of grid blocks [12, 16]. Several researchers have worked on block-to-block interactions and grid block shape factors under different conditions and assumptions [17-21]. The block-to-block interaction, especially in the case of gravity drainage, depends upon the degree of reimbibition among them. The re-entry of oil into matrix block, which has come from matrix to fracture, is termed reimbibition [17, 22]. Shariat *et al.* [23], under different limitations, studied the behavior of block-to-block interaction. They concluded that if capillary continuity exists among blocks, the vertical fracture permeability has an inadequate contribution to recovery.

2. Water Flooding in NFRs:

Most reservoirs contain initial immobile or mobile water depending on critical water saturation. There are also several cases when a water table or underlying aquifer can influence oil recovery. Similarly, reservoirs can be subjected to water injection or flooding to increase hydrocarbon recovery. In NFRs, water flooding generally acts as a beneficial driving mechanism [15, 24, 25]. Water flooding is done by injecting water at the suitable position(s) of the reservoir so that water displaces the oil [26]. Beliveau *et al.* [27] evaluated the NFR field of Canada by water injection scenarios. Their results showed that water imbibition has a major role in matrix-fracture fluid transferability compared to the gravity drainage process. When water is injected, firstly, it surrounds the matrix medium and then attempts to move the oil out of the matrix. Oil displacement by water is mainly due to the imbibition of water into the matrix block under capillary action for water-wet rock. The capillary forces allow the entry of water, and oil is displaced. Due to the density difference between water and oil, gravity effects also play a vital role in recovery. Aljuboori et at. [28] investigated the effectiveness of low salinity waterflooding in NFR's while performing numerical simulations. They generated the flow curves using the published work and applied these to simulate water flooding using fine-scale and field-scale models, and concluded that the oil recovery in fractured reservoirs can be increased by low salinity waterflooding. Abdul Salam *et al.* [29] performed the numerical modeling of NFR's to quantify the oil recovery through imbibition process using a fully implicit Mimetic Finite Difference (MFD) approach. They observed that the oil recovery is highly dependent on the wetting condition of the rock along with the alignment of natural fractures and concluded the MFD method to be vigorous in accurately analyzing the discrete-fractured reservoirs. Karimova *et al.* [30] reviewed the experimental and numerical studies of implementing low-salinity water injection and recommended to perform analysis of wettability alternation due to co/counter-imbibition during the development of NFR numerical models.

2.1 Research Objectives:

Matrix block shapes generally used in theoretical explanations include cubical, slab, and matchstick types [12]. Typically, a cubical shape is used for discussion and simulation purposes. However, the fluid flow behavior in this multi-porosity system from matrix to fracture depends on the block shape. The fluid flow entering the fracture system is governed by fracture capillary pressure, which is strongly believed to be non-existent and has been neglected during simulation studies.

In this work, simulation studies have been conducted while considering different block shapes and incorporating fracture capillary pressure as a function of matrix capillary pressure for in-depth analysis and to investigate the influence of such factors on fluid flow dynamics and recovery.

3. Case Study:

3.1 Reservoir Model Description:

The NFR model is developed by initially considering the grid block shape as cubical (base case). The dimensions for the cube are 40 ft, with an effective vertical length of 10 ft. The reservoir depth is 7000 ft, and the formation thickness is 320 ft. Pressure at the datum depth is 3458 psi, and water-oil contact is at 7250 ft. Four productions and one injection well have an inverted five-spot pattern, whose schematic view is shown in Figure 1. The other relevant reservoir data is given in Table 1, and capillary pressure data is provided in Figure 2.

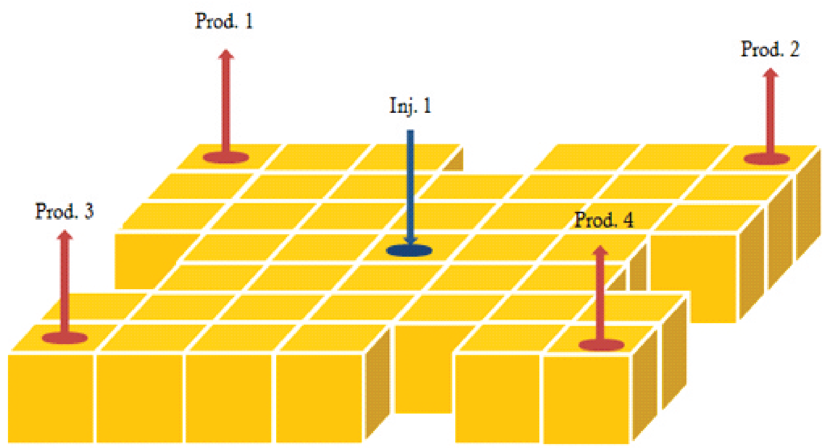

Figure 1: Schematic well location for injection and production wells

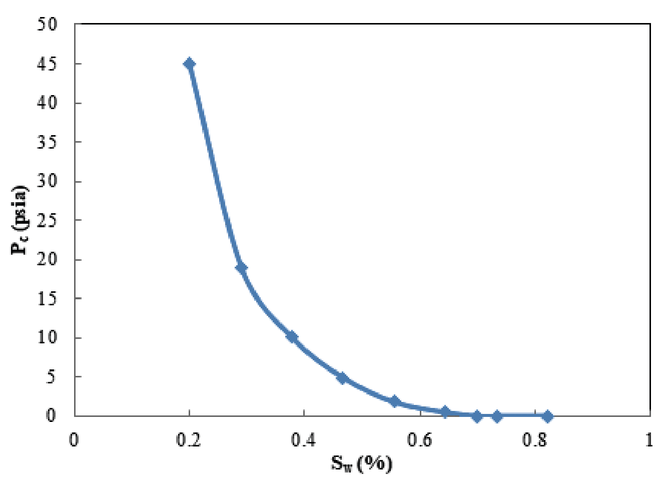

Figure 2: Capillary pressure data

Later, the reservoir model shape is changed into slab and matchstick grid block shapes, keeping all factors the same as in the case of cubical in order to achieve comparative results.

3.2 Simulation Study:

The reservoir modeling has been conducted using a commercial black oil simulator. The study is divided into the following cases and scenarios;

1) The reservoir model is prepared considering a standard grid block shape, i.e., cubical, and assuming fracture capillary pressure (P_{cf}) as zero. Variations in grid block shapes are done by changing the grid blocks as slabs and matchsticks. The dimensions of x, y, and z are set according to the desired grid block shapes. The shapes are adjusted in such a way that the total oil in place remains the same. Also, the contribution of fluid flow of each matrix block towards the fracture network remains the same according to Kazmi *et al.*, [18] shape factor, which can be written as equation (1);

$$\sigma = 4\left(\frac{1}{L_x^{\,2}} + \frac{1}{L_y^{\,2}} + \frac{1}{L_z^{\,2}}\right) \ldots\ldots\ldots\ldots\ldots\ldots (1)¶$$

2) Further, different scenarios have been prepared for each grid block shape during simulation studies by varying P_{cf} as a function of the matrix capillary pressure (P_{cm}) curve, as shown in Figure 3, and its effects on recovery have been analyzed.

3) Comparison of results based on the cases as mentioned above and scenarios.

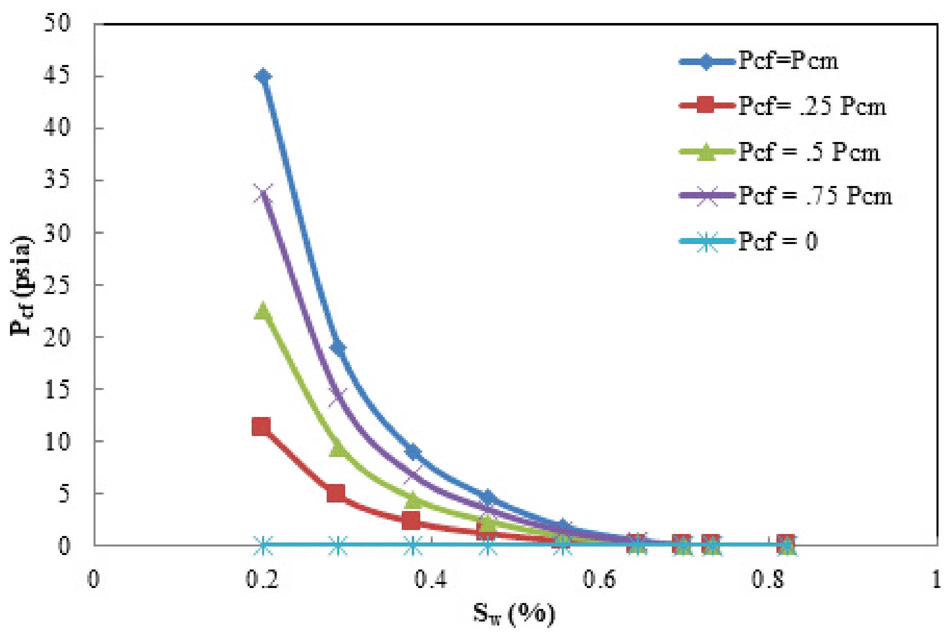

Figure 3: Variation of fracture capillary pressure (Pcf) with respect to matrix capillary pressure (Pcm)

4. Results And Discussions:

4.1 Cases of Grid Block Shapes

4.1.1 Case 1

In case 1, the grid block shape is taken as cubical, and capillary pressure in fractures is taken as zero, which is a general assumption during NFR simulation studies. The Vvariations of capillary pressure are made in fractures capillary pressure relative to matrix capillary pressure in scenarios (section 4.2), and their effects on recovery are also analyzed.

4.1.2 Case 2

In case 2, the slab-type grid block is adopted. The slab shape of grid blocks are formed by varying x, y, and z dimensions. Fracture capillary pressure is taken as zero, keeping all the other factors the same as in case 1.

4.1.3 Case 3

In this case, the matchstick grid block shape is made having zero fracture capillary pressure. The shape is made by reducing the x and y dimensions and increasing the z dimension of the grid block.

4.1.4 Comparative Results of Cases

A comparison has been established showing the results of the above-mentioned cases in the form of field oil production rate, average field pressure, field water cut, and oil recovery.

Oil production and water cut are shown in Figure 4 for each grid block shape. The sharp decline in early days of production for each grid block shape shows the oil production only through fractures and during this time matrix blocks do not contribute to production. With the passage of time, matrix start to contribute to oil production and the trend increase. However, due to the depletion of matrix as well as fractures, the oil production trend declines. It is observed that oil production is more in the case of slab-type grid block shape. Capillary pressure is the same, and capillary forces will allow water entry in matrices. Since the slab block's height is less than other shapes, more water rises, and more oil is drained from the matrix blocks. Thus, more oil is produced for slab-type grid block shapes.

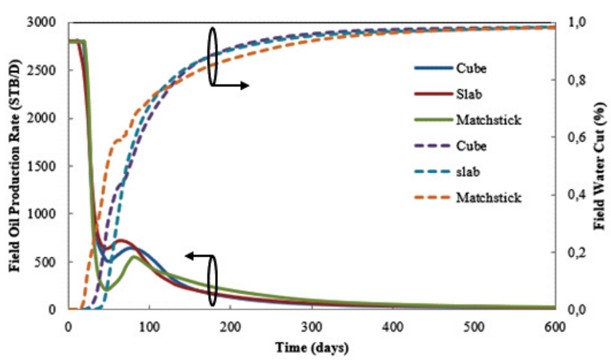

Figure 4: Comparison of field oil production rate and field water cut with time for different grid block shapes

Furthermore, due to the greater vertical height of fractures and less cross-sectional area exposed to water in matchstick grid blocks, water will rise faster than other block shapes. Early water cut is achieved in matchstick shape and relatively late in slab and cubical grid block shapes. Figure 5 compares pressure drop with time for different grid block shapes. In the matchstick grid block, fractures deplete more quickly, which creates more pressure drop than the other grid block.

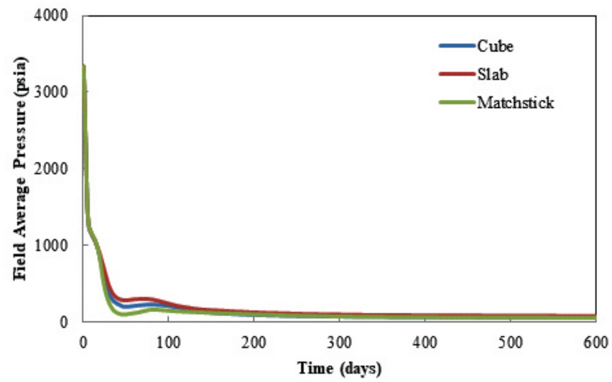

Figure 5: Comparison of field average pressure with time for different grid block shapes

As discussed earlier, more oil is produced through slab-type grid block shapes, so recovery by this shape is more significant than other grid block shapes. Water imbibes more quickly in slab-type grid block due to the more area exposure and less oil head in slab matrix blocks. Therefore, less resistance by the oil head is exhibited in slab blocks compared to other block shapes. The comparative results are shown in Figure 6.

Higher oil production is achieved by considering slab grid block shape and hence the more remarkable recovery, as shown in Figure 7.

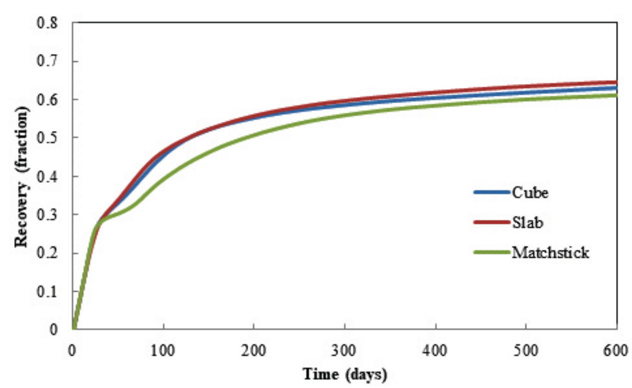

Figure 6: Comparison of recovery with time for different grid block shapes.

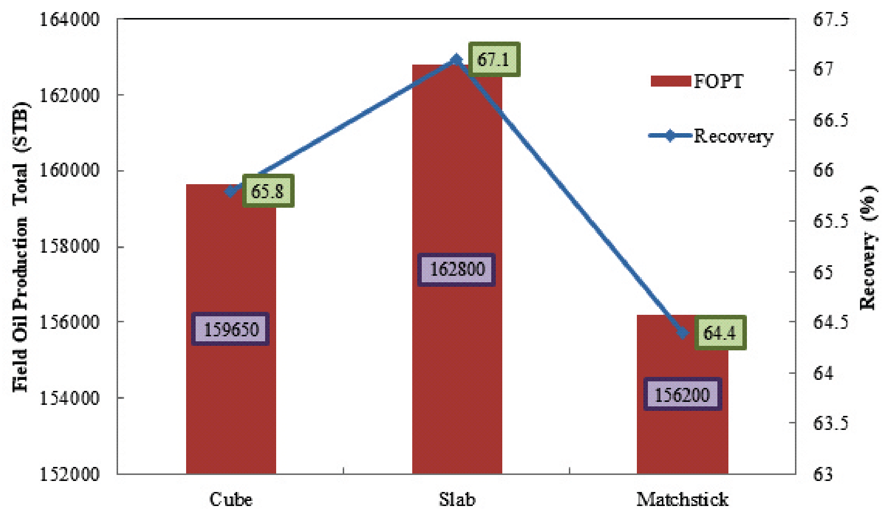

Figure 7: Comparison of total oil production and recovery for different grid block shapes.

4.2 Fracture Capillary Pressure Scenarios:

4.2.1 Scenario 1:

In this scenario, the grid block shape is taken as cubical, and variations are done in fracture capillary pressure relative to the matrix capillary pressure.

Figure 8 shows the recovery achieved for different fracture capillary pressures (P_{cf}) concerning matrix capillary pressures (P_{cm}). It can be seen that as the fracture capillary pressure increases, recovery is decreased. It is because when interacting forces present between the two phases, which are oil and water in this case, increase, there will be an increase in resistance to flow. Hence, the recovery is decreased.

4.2.2 Scenario 2:

In this scenario, slab grid block shape is adopted, and simulation is done by taking fracture capillary pressures, as mentioned in scenario 1. Figure 9 shows variations in recovery for different fracture capillary pressures. The trend is somewhat the same as in Figure 8.

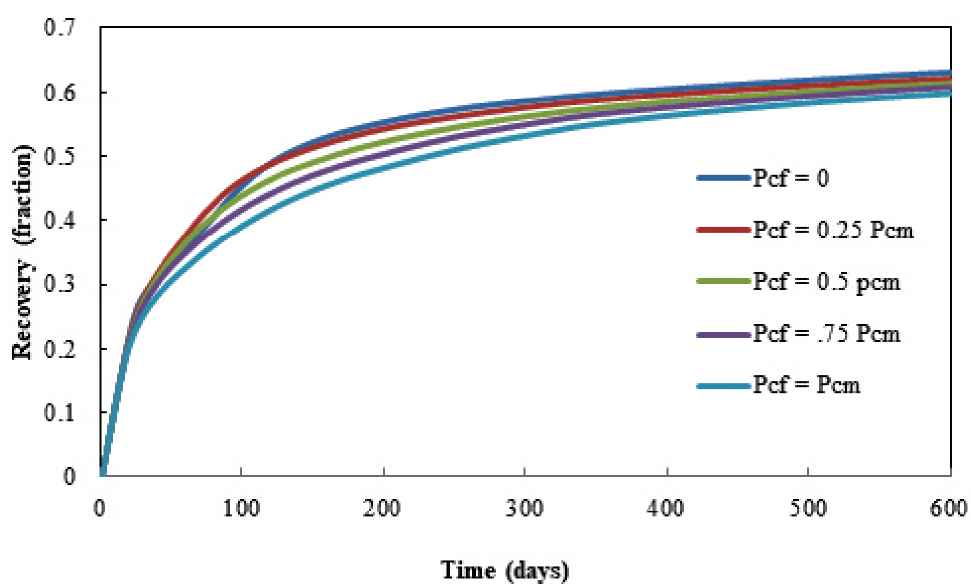

Figure 8: Recovery with time for different fracture capillary pressures for cube

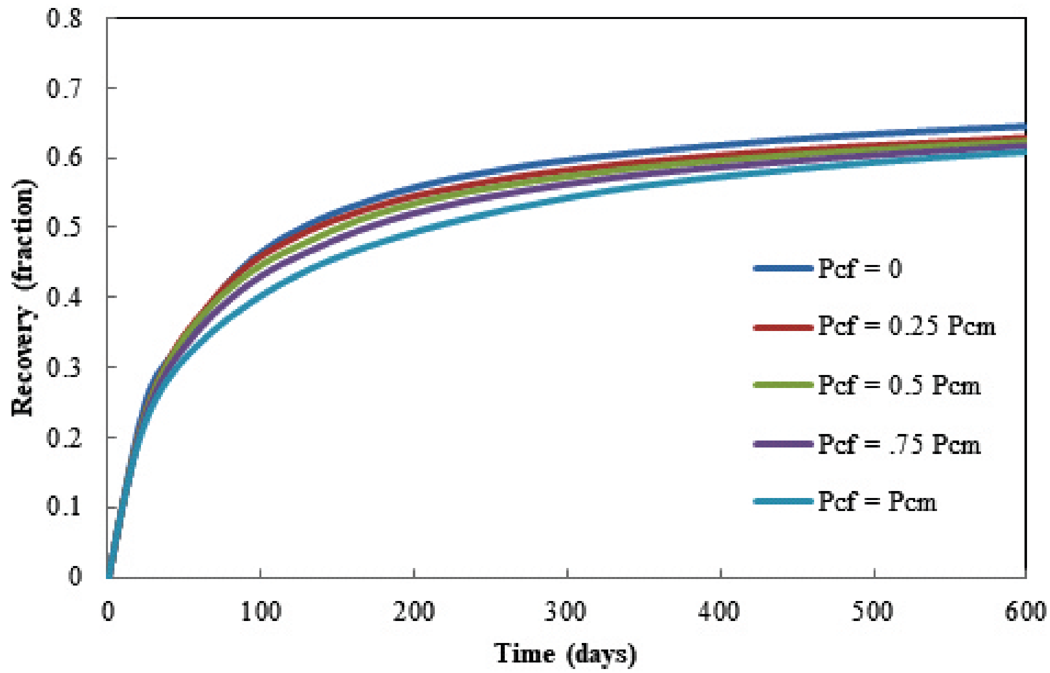

Figure 9: Recovery with time for different fracture capillary pressures for slab

4.2.3 Scenario 3:

Scenario 3 represents the modeling of the reservoir by taking the grid block shape as the matchstick, and the same fracture capillary pressure variations are applied to check the effects on recovery. Figure 10 shows the recovery relationship with time for the matchstick grid block shape. Figure 11 describes the comparative results of the scenarios indicating the decreasing trend in recovery as fracture capillary pressure is increasing in each grid block shape.

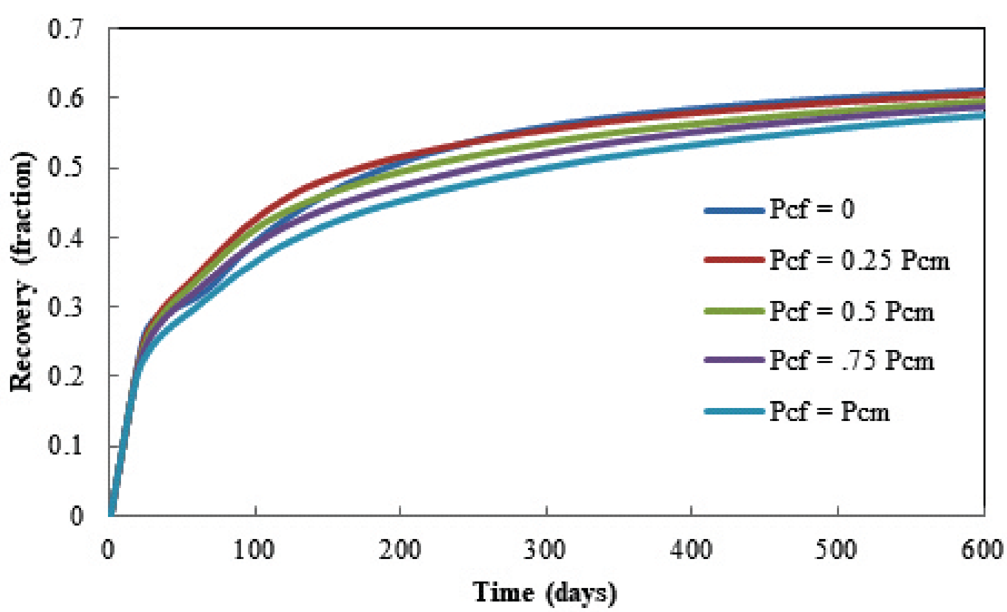

Figure 10: Recovery with time for different fracture capillary pressures for matchstick

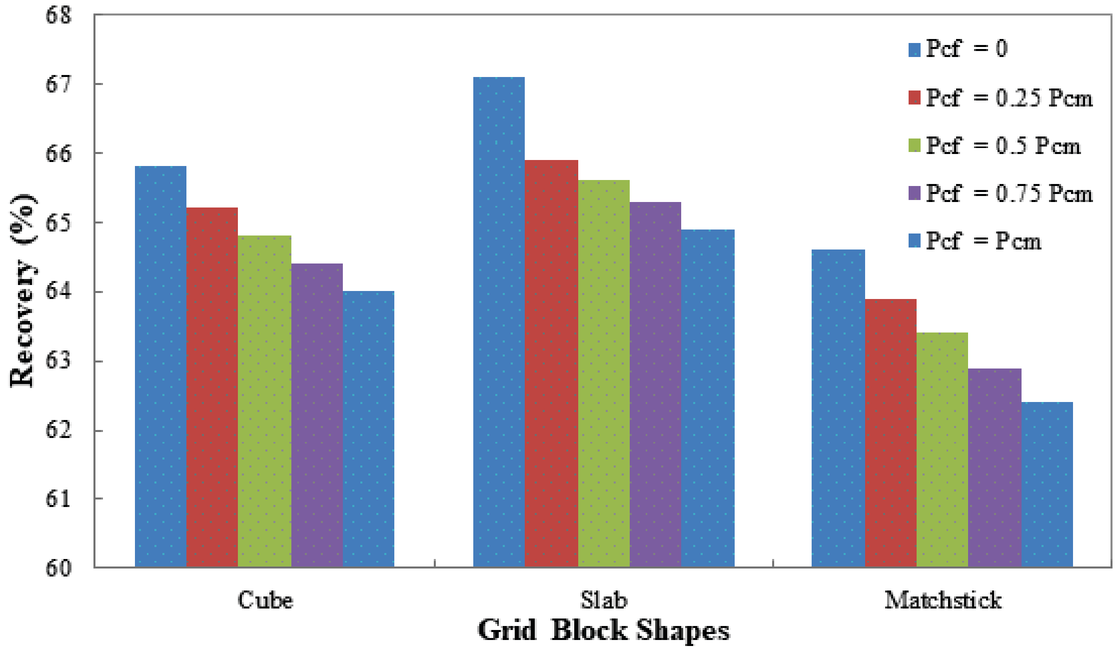

Figure 11: Comparative results of scenarios

Table 1: Reservoir model description

Reservoir Fluids	Oil, Gas, Water
Number of Grid Blocks	7x 7x 8
Matrix Porosity	0.2
Matrix Permeability	3.2 mD
Fracture Porosity	5.0 %
Fracture Permeability	10000 mD
Production well location	(1,1)(1,7)(7,1)(7,7)
Injection well location	(4,4)

5. Conclusions:

Based on this research work, it has been observed that by changing the grid block shape, hydrocarbon recovery is changing. Recovery has an inverse relationship with grid block height. As in the case of slab-type grid block shapes, block height is low, and recovery is greater than other grid block shapes. It is also observed that variation in fracture capillary pressure has an impact oil flow, reducing the oil flow rate. Also, an increase in fracture capillary pressure is causing a decrease in oil recovery. While conducting numerical simulation studies of NFRs, it is recommended to incorporate the variations in grid block shapes. Moreover, emphasis should be given to checking fracture capillary pressure effects during the simulation of naturally fractured reservoirs.

Nomenclature:

ϕ	Porosity, (-)
k	Permeability, (mD)
P_{cf}	Fracture capillary pressure, (psi)
P_{cm}	Matrix capillary pressures, (psi)
L_x	Length of matrix block in x-direction, (ft)
L_y	Length of matrix block in y-direction, (ft)
L_z	Length of matrix block in z-direction, (ft)
σ	Shape Factor, (-)

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