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Modelling of gas transport in fractured coal seam

Coalbed methane is found almost everywhere, where coal located. Its concentration in the mixture of natural gas coal seams is 80 - 98, and the scope of resources are comparable with resources conventional gas fields in the world. The coalbed methane reservoir is treated as a system consisting of coal matrix and fracture network. Methane from the matrix diffuses through the micropores into fracture and further goes to production wells. The flow of gas and water in the fracture is described by Darcy's equation. Most existing coalbed methane simulators usually treat coal seams as dual-porosity, single-permeability systems ignoring the effects of water presence in the coal matrix. In this study, a compositional dual-porosity, dual-permeability CBM simulator has been developed. The new model allows considering fluid expansion and imbibition recovery mechanisms for coal seam. The influence of the capillary forces during imbibition on the final recovery factor was investigated. In this paper a new model was constructed on DuMux and compared with Comsol.
Key words: Coalbed methane; Matrix-fracture system; DuMux; Comsol; Reservoir simulation.

Ф.А. Хамитов, Д.Ж. Ахмед-Заки

Моделирование переноса газа в угольном пласте

Метан угольных пластов встречается практически везде, где залегает уголь. Его концентрация в смеси природных газов угольных пластов составляет 80 - 98, а масштабы ресурсов соизмеримы с ресурсами газа традиционных месторождений мира. Угольный пласт, рассматривается как система, состоящая из матрицы угля и сети трещин. Метан, содержащийся матрице, диффундирует через микропоры в трещины, и далее по трещинам поступает в добывающие скважины. Течение газа и воды в трещинах описывается уравнением Дарси. Большинство существующих программных продуктов по моделированию метана угольных пластов обычно рассматривают угольный пласт как систему с двойной пористостью и с одинарной проницаемостью, игнорируя эффекты присутствия воды в угольной матрице. В данной работе разработана модель с двойной пористостью и двойной проницаемостью. Новая модель позволяет учитывать механизмы расширения жидкости и пропитки угольной матрицы. Исследовано влияние капиллярных сил в процессе пропитки на конечный коэффициент отдачи. Построенная на DuMux модель сравнена с результатами моделирования в Comsol.
Ключевые слова: Метан угольного пласта; Система матрица - трещина; DuMux; Comsol; Разработка месторождения.

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Көмір қыртысындағы газ тасымалын модельдеу

Көмір қыртысындағы метан іс жүзінде тас көмір жатқан жыныстарының барлығында кездеседі. Метанның көмір қыртысындағы табиғи газдардағы концентрациялық мөлшері 80-98 құрайды, ал ұндірістық ресурстары дуние жүзі әдеттегі газдар ресурстарымен салыстырмалы. Құрамында метан бар көмір қыртысы көмір матрицасынан және сызаттар жүйесінен тұратын жүйе ретінде қарастырылған. Көмір матрицасында орналысқан метан диффузиялық процесс арқылы микроөткізгіштерден сызаттарға, әрі қарай өндіріс ұңғымасыларына өтеды. Сызаттардағы газ және су ағымы Дарси теңдеуімен жіктеледі. Көмір қыртысындағы метанды модельдейтін көптеген бағдарламалық жасақтамалар, әдетте көмір қыртысын көмір матрицасында бар су әсерін ескермей, қос кеуектілігі және бір өткізгіштігі бар жүйе ретінде қарастырады.

Бұл жұмыста қос кеуектілігі және қос өтгізгіштігі бар модель жасалған. Жаңа құрастырылған модель сұйықтың көбею механизмін және көмір матрицасының ылғалдануын ескеруге мүмкіндік береді. Ылғалдану кезіндегі капиллярлы күштердің алудың соңғы коэффициентіне әсері зерттелген. DuMux бағдарламасында құрылған модель Comsol бағдарламасында алынған нәтижелермен салыстырылды.
Түйін сөздер: Көмір қыртысындағы метан; Матрица-сызат жүйесі; DuMux; Comsol; Кен орнын әзірлеу

Introduction

The Coal Bed Methane (CBM) is one of unconventional resource of natural gas, which is reserved in coal seams. Such reservoirs are usually naturally fractured and characterized as a dual porosity medium composed of fractures (cleats) and matrix. The mechanism for gas flow in the coal involves two steps: diffusion of the gas through the micropores, and Darcy flow through the fracture network to the wellbore. The most commonly used flow model for practical simulations of fractured systems is the dual-porosity model. Here the basic idea is to dissociate the flow inside the fracture network and the matrix and to model the exchange between these two media using a transfer function. This concept was first introduced by Barenblatt and Zheltov [4]. After this was proposed the model by Warren and Root [1], the fractured reservoir presented as a rectangular parallelepipeds, separated by a rectangular network of fracture (Fig 1), model focused on the evaluation of the transfer function τ. Models of this type were first introduced by Blaskovich et al. (1983) and Hill and Thomas (1985). By adding the matrix to matrix connections, the matrix blocks are no longer isolated, and contribute to the overall fluid flow. Being more general than the dual-porosity model, which is limited to strongly connected fractured reservoirs, the dual-porosity/dual-permeability model is capable of simulating a wide variety of problems ranging from slightly fractured to highly fractured systems. The model suggests conventional flow between matrix cells. This model was implemented in a free open-source code for flow and transport processes in porous media, DuMux, which is based on the Distributed and Unified Numeric Environment (DUNE)[5,6].

Governing equations

Two-phase dual porosity and permeability model, which uses a standard Darcy approach as the equation for the conservation of momentum:

$$\begin{cases} \frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha)_m - div(\rho_\alpha K\frac{\kappa_\alpha}{\mu_\alpha}[gradP_\alpha])_m + \tau_{\alpha FM} = 0 \\ \frac{\partial}{\partial t}(\phi\rho_\beta S_\beta)_m - div(\rho_\beta K\frac{\kappa_\beta}{\mu_\beta}[gradP_\beta])_m + \tau_{\beta FM} = 0 \\ \frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha)_f - div(\rho_\alpha K\frac{\kappa_\alpha}{\mu_\alpha}[gradP_\alpha])_f - \tau_{\alpha FM} = 0 \\ \frac{\partial}{\partial t}(\phi\rho_\beta S_\beta)_f - div(\rho_\beta K\frac{\kappa_\beta}{\mu_\beta}[gradP_\beta])_f - \tau_{\beta FM} = 0 \end{cases} \quad (1)$$

Where ϕ is porosity; $\rho_\alpha-$ density, $S_\alpha-$ saturation, $P_\alpha-$ pressure, $\mu_\alpha-$ viscosity, $\kappa_\alpha-$ relative permeability of α phase; $K-$ absolute permeability; f and m are respectively fracture and matrix systems;This model contains transfer term,τ is the exchange between the matrix and the fracture that can be determined by [3]:

$$\tau_{\alpha FM} = \frac{K_m\kappa_{r\alpha}(S_{\alpha m})\rho_{\alpha m}\sigma}{\mu_{\alpha m}}(P_f^\alpha - P_m^\alpha) \quad (2)$$

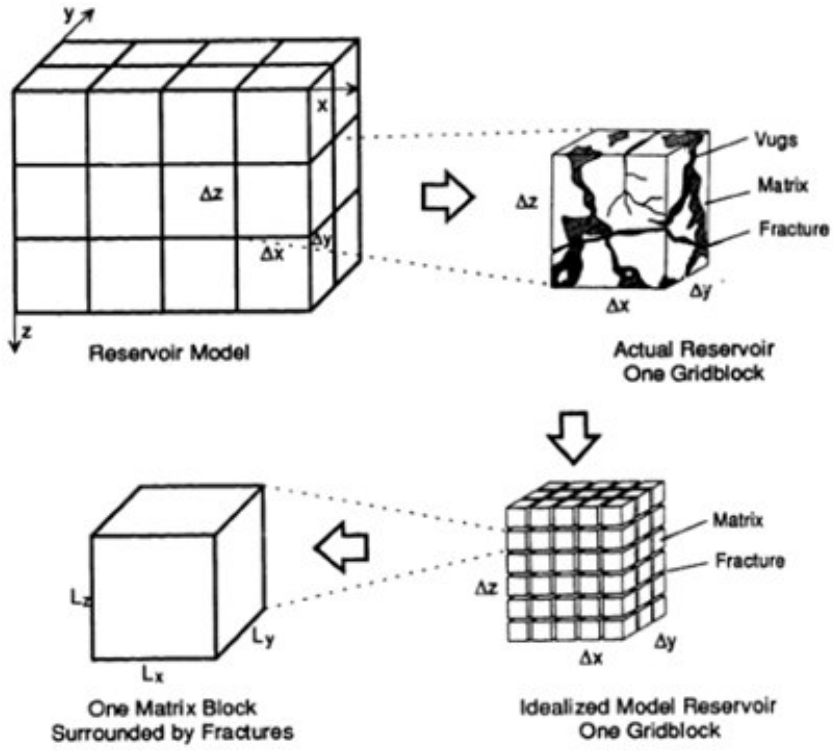

Figure 1 – Idealization of the NFR system (Warren and Root, 1963)

where σ was defined as a parameter representing the characteristic of the fractured rock [2]. The parameter σ has the dimension of reciprocal area, and is commonly known as the shape factor. Models of this type are well-suited for some purposes but are limited in their ability to resolve transient and multiphase flow phenomena, as spatial variation within the matrix is not modeled.

Reduction to dimensionless form

The dimensionless variables are:

$$\overline{P}_{\alpha f} = \frac{P_{\alpha f}}{P_*}, \overline{P}_{\alpha m} = \frac{P_{\alpha m}}{P_*}, \overline{t} = \frac{t}{t_*}, \overline{x} = \frac{X}{L}, \overline{K}_m = \frac{K_m}{K_*}, \overline{K}_f = \frac{K_f}{K_*}, \overline{\mu}_{\alpha f} = \frac{\mu_{\alpha f}}{\mu *}$$

$$\overline{\mu}_{\alpha m} = \frac{\mu_{\alpha m}}{\mu *}, \overline{\phi}_f = \frac{\phi_f}{\phi_*}, \overline{\phi}_m = \frac{\phi_m}{\phi_*}, \overline{\rho}_{\alpha f} = \frac{\rho_{\alpha f}}{\rho_*}, \overline{\rho}_{\alpha m} = \frac{\rho_{\alpha m}}{\rho_*} \tag{3}$$

Eq. 1 in one-dimensional case transforms into:

$$\begin{cases} \frac{\partial}{\partial \overline{t}}(\overline{\phi}\overline{\rho}_\alpha S_\alpha)_m \frac{\phi_*\rho_*}{t_*} - \frac{\rho_* P_* K_*}{\mu_* L^2} div(\overline{\rho}_\alpha \overline{K} \frac{\kappa_{r\alpha}}{\overline{\mu}_\alpha}[grad\overline{P}_\alpha])_m + \frac{\rho_* P_* K_*}{\mu_*} \cdot \frac{\overline{K}_m \kappa_{r\alpha}(S_{\alpha m})\overline{\rho}_{\alpha m}\sigma}{\overline{\mu}_{\alpha m}}(\overline{P}_f^\alpha - \overline{P}_m^\alpha) = 0 \\ \frac{\partial}{\partial \overline{t}}(\overline{\phi}\overline{\rho}_\beta S_\beta)_m \frac{\phi_*\rho_*}{t_*} - \frac{\rho_* P_* K_*}{\mu_* L^2} div(\overline{\rho}_\beta \overline{K} \frac{\kappa_{r\beta}}{\overline{\mu}_\beta}[grad\overline{P}_\beta])_m + \frac{\rho_* P_* K_*}{\mu_*} \cdot \frac{\overline{K}_m \kappa_{r\beta}(S_{\alpha m})\overline{\rho}_{\beta m}\sigma}{\overline{\mu}_{\beta m}}(\overline{P}_f^\beta - \overline{P}_m^\beta) = 0 \\ \frac{\partial}{\partial \overline{t}}(\overline{\phi}\overline{\rho}_\alpha S_\alpha)_f \frac{\phi_*\rho_*}{t_*} - \frac{\rho_* P_* K_*}{\mu_* L^2} div(\overline{\rho}_\alpha \overline{K} \frac{\kappa_{r\alpha}}{\overline{\mu}_\alpha}[grad\overline{P}_\alpha])_f - \frac{\rho_* P_* K_*}{\mu_*} \cdot \frac{\overline{K}_m \kappa_{r\alpha}(S_{\alpha m})\overline{\rho}_{\alpha m}\sigma}{\overline{\mu}_{\alpha m}}(\overline{P}_f^\alpha - \overline{P}_m^\alpha) = 0 \\ \frac{\partial}{\partial \overline{t}}(\overline{\phi}\overline{\rho}_\beta S_\beta)_f \frac{\phi_*\rho_*}{t_*} - \frac{\rho_* P_* K_*}{\mu_* L^2} div(\overline{\rho}_\beta \overline{K} \frac{\kappa_{r\beta}}{\overline{\mu}_\beta}[grad\overline{P}_\beta])_f - \frac{\rho_* P_* K_*}{\mu_*} \cdot \frac{\overline{K}_m \kappa_{r\beta}(S_{\alpha m})\overline{\rho}_{\beta m}\sigma}{\overline{\mu}_{\beta m}}(\overline{P}_f^\beta - \overline{P}_m^\beta) = 0 \end{cases}$$

(4)

Additionally, Eq. 4 required defining the relative permeability functions. The most common correlation was invented by Brooks and Corey in 1964 [8]. We used a simpler form:

$$\begin{cases} \kappa_{rw}(S) = (S)^{\frac{2+3\lambda}{\lambda}} \\ \kappa_{rn}(S) = (1-S)^2(1-S^{\frac{2}{\lambda}+1}) \end{cases} \tag{5}$$

Where λ is some parameter, in this case =2.0 .

Implementation

The problem considers two different domains the matrix and fracture and for each of them initial and boundary conditions are different:

$$\begin{cases} \overline{P}_m = \overline{P}_f = \overline{P}_0 = 1.2; S_m = 0; S_f = 1 for(\overline{t} = 0, 0 < \overline{x} < 1) \\ \overline{P}_m = \overline{P}_f = 1.2; S_m = S_f = 0 for(\overline{x} = 0) \\ \overline{P}_f = 0.1; S_f = 1 for(\overline{x} = 1) \end{cases} \tag{6}$$

We assumed that the matrix domain consist only nonwetting phase (gas) and the fracture system include wetting phase (water). By default putted the Neumann boundary condition, that means no flow on the all boundary and in the second place we change left and right boundaries by Dirichlet boundary condition (see Eq.6). The standard DuMux complectation has not necessary Warren and Root dual porosity model [1] and we develop new model that correspond to Eq.4 [5]. DuMux extensively uses all advantages of object oriented programming. In practice, this means possibility of using the all other modules like grid, parallel computations, visualization etc. To verify the solutions obtained on the Dumux simulator used a results taken from similar model in Comsol [7].

Comparison of the results

Verification of the constructed model on DuMux includes the consideration of many cases with different input parameters. Generally the model have to be buildable in each cases, but input parameters should be taken based on real physical process. We will focus on the consideration the case includes following input parameters:

- The boundary and initial conditions as in Eq. 4.
- The two dimensional computational area contains 75•150 cells

Obtained results were compared with output Comsol's data. The constructed in Comsol model is identical to DuMux model and used the same computational grid and input conditions. Based on theoretical solution [9] we can do conclusion that DuMux looks more attractive (see Fig. 2). The maximum relative errors between solutions (see Fig. 3 and Fig. 4) constitute 15 % for pressure in fracture and 0.2 % for pressure in matrix at the last modelling timestep.

Model based on capillary forces

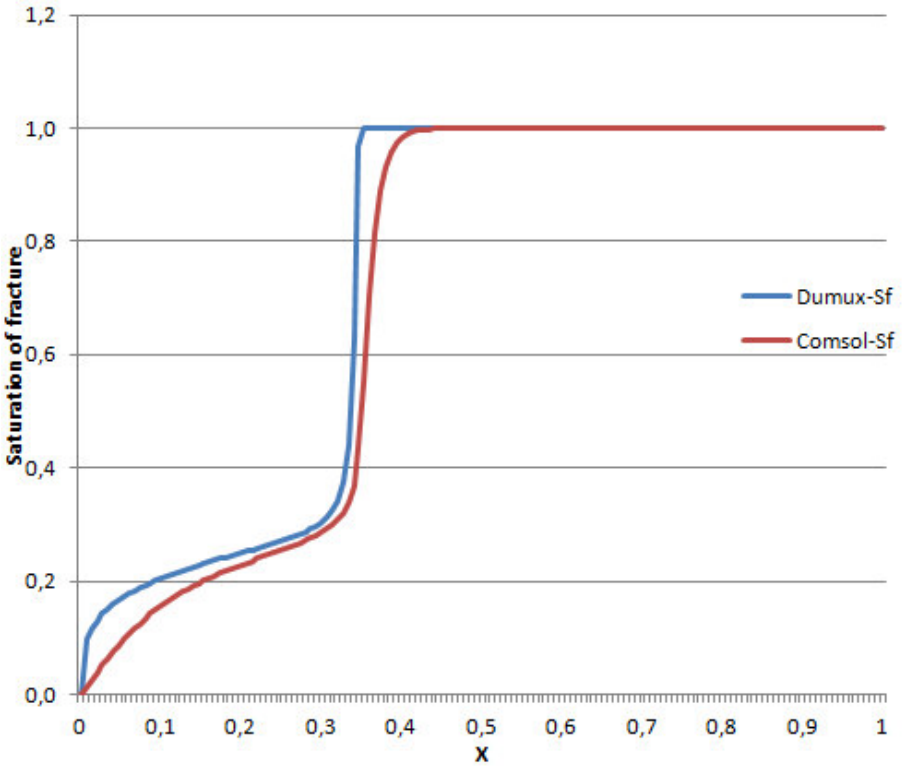

Figure 2 – Matching of saturation wetting phase in fracture by DuMux and Comsol

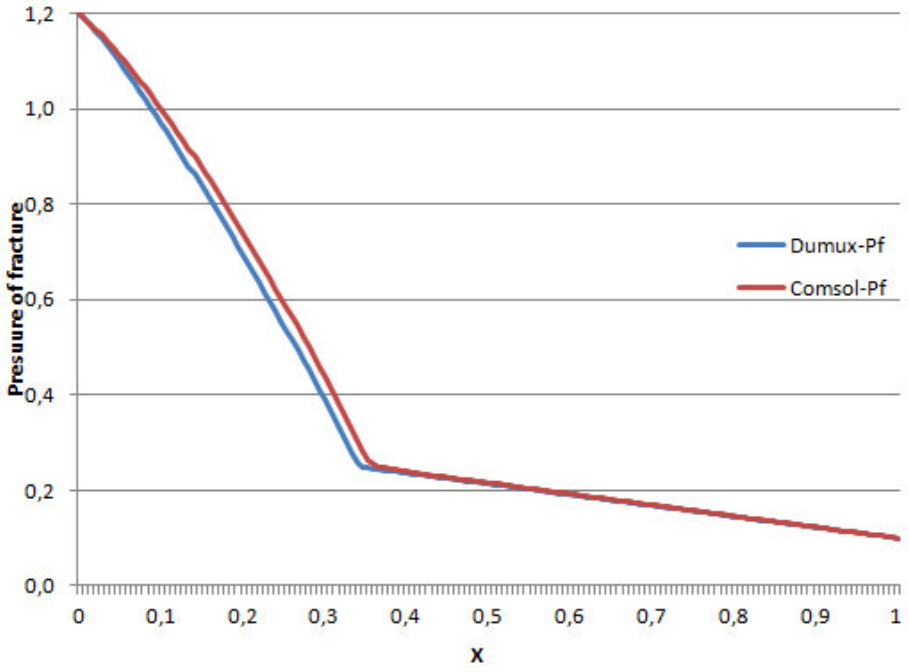

Figure 3 – Matching of pressure in fracture by DuMux and Comsol

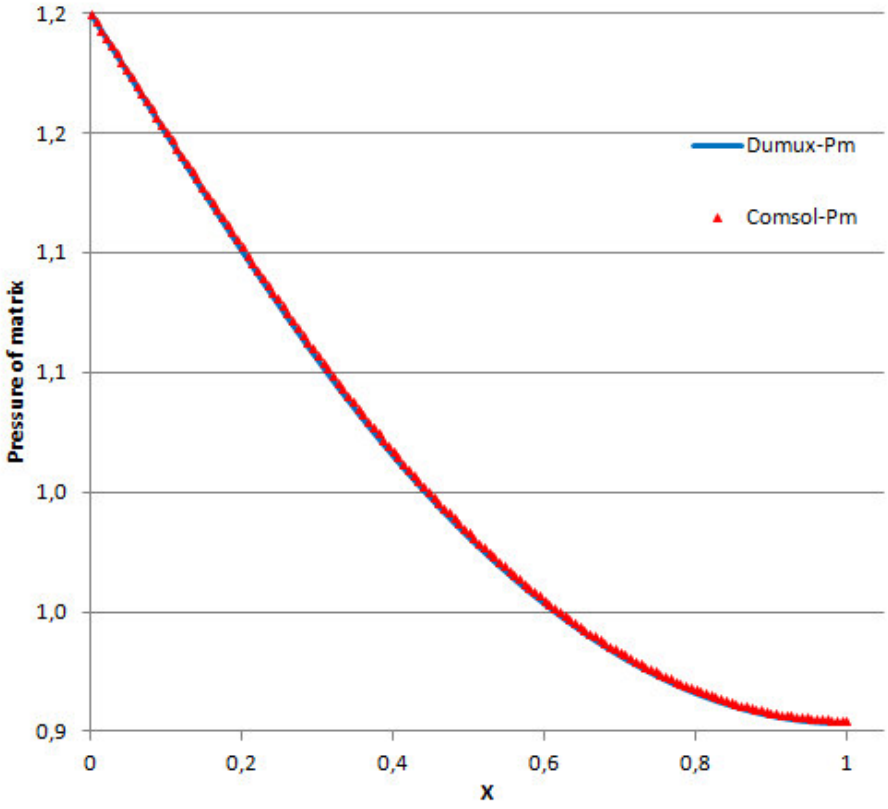

Figure 4 – Matching of pressure in matrix by DuMux and Comsol

Model that corresponds to the system of Eq.4, does not account for the effect of capillary forces. Capillary forces can be given by tabular dates or by empirical formulas, here was used a model Brooks and Corey in 1964 [8]:

$$P_c = P_{ct}(\frac{1 - S_{or}}{S - S_{or}})^{\frac{1}{\lambda}} \tag{7}$$

S_{or} is the residual oil saturation that remains trapped in the pore at high capillary pressure.P_{ct}, the threshold pressure, corresponds approximately to the pressure at which the nonwetting phase is sufficiently connected to allow flow. Brooks and Corey related the parameter λ to the distribution of pore sizes. Where λ is some parameter, in this case =2.0. Generally capillary pressure in the fracture in the matrix may correspond to different empirical equations, but for simplicity we have used Eq.7 matrix and fracture. The boundary conditions were chosen under condition that the initial state of the reservoir contains a nonwetting fluid, which is produced at the constant production rate on the right, and on the left bordered with a wetting phase.

$$\begin{cases} \overline{P}_m^w = \overline{P}_f^w = \overline{P}_0 = 1.7; S_m^n = S_f^n = 1 for(\overline{t} = 0, 0 < \overline{x} < 1) \\ \overline{P}_m^w = \overline{P}_f^w = 1.7; S_m^n = S_f^n = 0 for(\overline{x} = 0) \\ \overline{q}_f^n = 7.5e - 2 for(\overline{x} = 1) \end{cases} \tag{8}$$

Where w-wetting phase, n-nonwetting phase and q- flow rate Two-dimensional graphs of

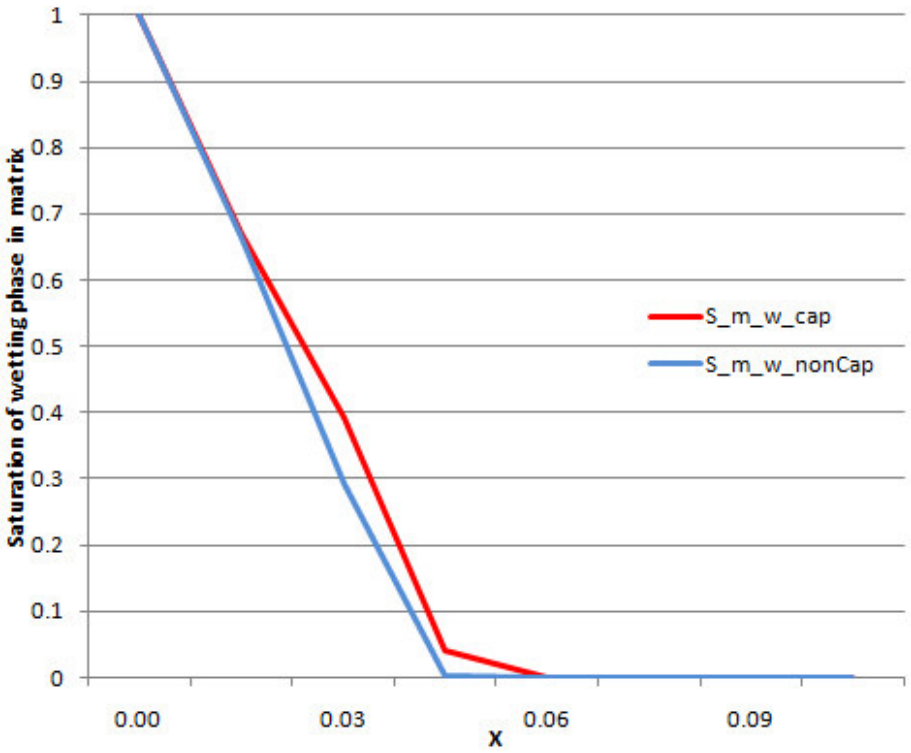

Figure 5 – Saturations of wetting phase in matrix for different cases

saturations are shown in Fig.7. The computational area contains 65•65 cells. The results of modeling (red curve) were compared with basic model (blue curve), that corresponds to the system of Eq.4, but with new boundary conditions Eq.8 (see Fig.5 and Fig.6). The figures show the saturations of the wetting phase in the matrix and fracture at the last timestep. Front of the saturation in the fracture is changing faster because at the time when the waterfront reaches the matrix, pressure in the fracture is reduced by reducing the capillary forces and increased delivery non-wetting phase into the fracture from the matrix. This process is called imbibitions. In a typical water wet (wetting phase) system the matrix rock has a positive water-oil capillary pressure. If water is introduced into the fracture, the water flows under capillary forces into the matrix system, displacing oil(non wetting phase) [10]. Consideration of the different physical mechanisms in enhanced oil recovery model leads to a better understanding of the process of production and helps to determine the optimal regimes of field development. So, accounting of the capillary forces in the model leads to increasing recovery factor from 2.24% to 2.46% in the matrix and from 15.02% to 16.01% respectively in the fracture.

Conclusion

The constructed on the DuMux immiscible two-phase dual porosity dual permeability model was verified by Comsol Multiphysics. The new model allows considering fluid expansion and imbibition recovery mechanisms for coal seam. Fluid expansion mechanism includes transfer function that regulates the mass transfer between matrix and fracture systems depends on pressure. Imbibition mechanism present by using different capillary pressure in

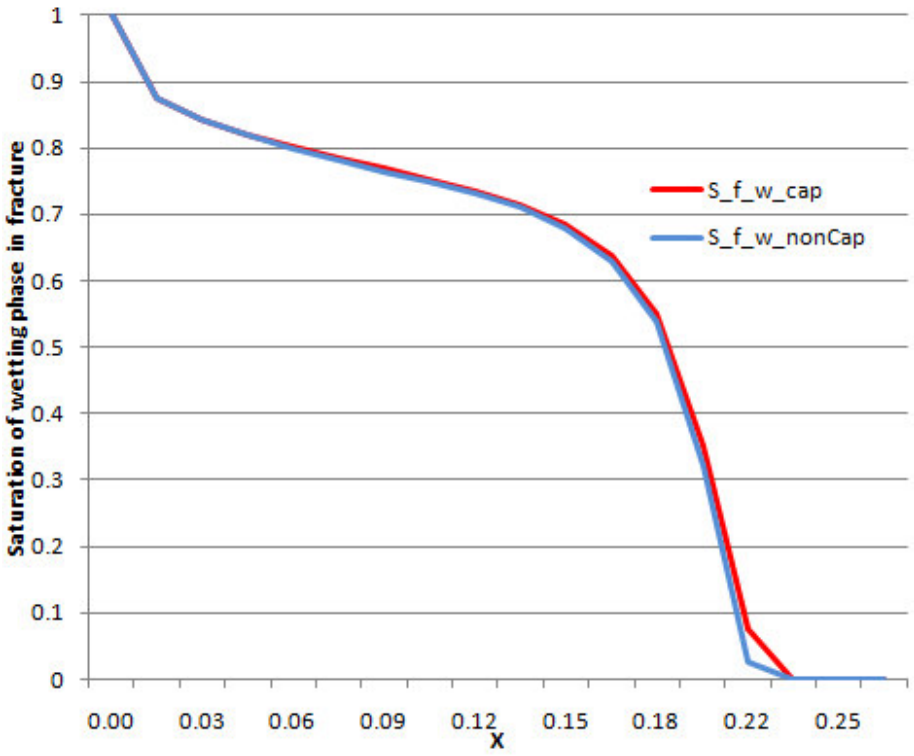

Figure 6 – Saturations of wetting phase in fracture for different cases

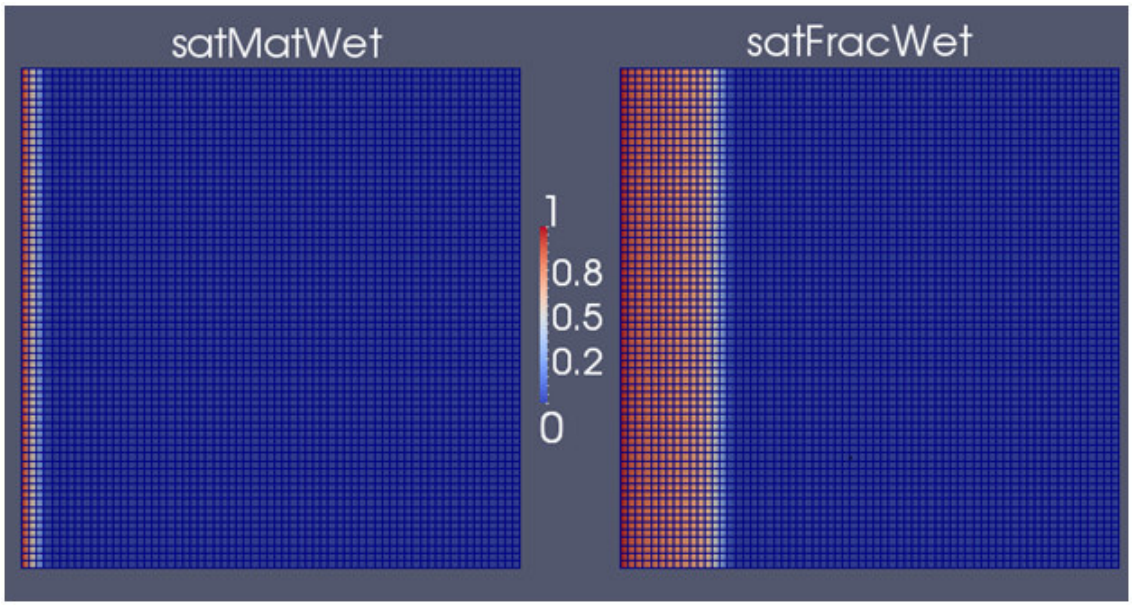

Figure 7 – Visualization results based on capillary forces on Paraview

matrix and fracture corresponds to their saturations. Consideration of the different recovery mechanisms in the model leads to significant effect on the recovery factor and gives a better understanding of the process of production helps to determine the optimal regimes

of field development. The designed module in DuMux allows taking full advantage of DuMux: different computational grids, a parallel computations, visualization, different numerical solvers.

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