Simulations of Gas Flow in a Coal Seam

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Abstract

Production of methane gas from coal seams is becoming very popular in the USA and also in Australia, as a natural source for clean gas. Coalbed methane (CBM) is classified as an unconventional reservoir, for which hydraulic fracturing is a commonly used stimulation technique to enhance production. A successful fracturing job is the one that provides maximum exposure to the natural fracture systems or cleats existing in the coal seam. The production from a coal seam depends highly on the permeability of both cleats and the coal itself.

Drilling horizontal wells within the reservoir layer will increase the exposure of the formation with the wellbore wall and therefore it is a desired well trajectory to be used for CBM production. Depending on the stress regime a hydraulic fracture initiated in a vertical or a horizontal well could propagate longitudinally within the coal layer or transversely where the fracture developes in a plane nearly perpendicular to the coal seam plane. Also, fluid flow behaviour would be different depending on the production type, i.e. openhole or cemented liner with perforations. For example, in case of production from a cemented horizontal well with few perforations in place, the fluid may travel a shorter distance within the hydraulic fracture, but there would be a significant flow convergence around the perforation tunnels before the gas enters into the wellbore. In production from a transversely oriented fracture, however, the gas will travel a long distance within the fracture plane and will converge around a very small wellbore: a high fluid velocity is expected in this case.

In this paper simple 2D simulations were carried out in order to investigate the change in production as a function of cleats and coal layer permeabilities. Also, the effects of cleat density and structures were studied. Change in flow behaviour as a result of horizontal drilling was investigated. Hydraulic fractures were considered in modelling and the results showed how gas flow will be improved by providing a larger exposure to the coal seam and intersecting larger number of cleats. Simulations were performed using ANSYS software. Designmodeler was used for model generation and FLUENT software was employed for flow analysis.

The results indicate the capabilities of FLUENT for flow simulation purposes where diferent fluid properties as well as wellbore and perforation geometries could be considered.

1. Introduction

Production from CBM reservoirs is considered as unconventional comparing to sandstone or carbonate reservoirs. In conventional reservoirs, hydrocarbons are generated in the source rock and migrate to the reservoir rock. Coal bed methane does not follow this pattern. Coals act as a source rock which are basically made of organic materials; moreover, coal cannot be considered as a conventional reservoir rock due to very low microporosity in the matrix of coals. In conventional reservoirs coal is often considered as cap rock; however, in CBM reservoirs, methane is adsorbed to the surface of the coal [Lea *et al*., 2008].

In CBM natural fractures in coal are called cleats which are categorised as face cleats and butt cleats(see Figure 1). Face cleats are the main and continous fractures which are the essential path for desorbed gas from matrix. Butt cleats are discontinous fractures usually perpendicular to face cleats [Morad *et al.*, 2008].

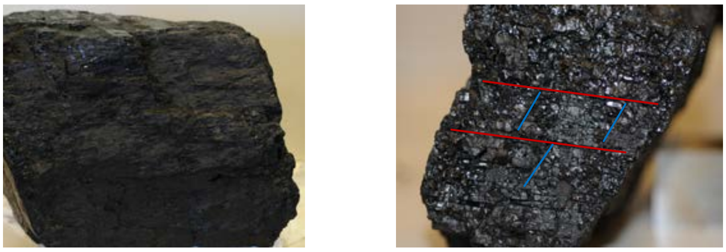


Figure 1: A coal block from an open pit mine in Queensland, with face (red) and butt (blue) cleats

Coal permeability in CBM is a function of permeability of cleats, therefore the structural and properties of cleat network like fracture orientation, spacing and width of cleats, especially face cleats are the main factor in controlling CBM permeability [Morad *et al.*, 2008].

CBM can be considered as a dual porosity system, micro pores in coal matrix and macro pore porosity of natural fractures (cleats). Most of the volume of gas is adsorbed to surface of coals, in order to desorb the gas high pressure drop is needed. De-watering cause pressure decline which desorb the gas from coal. The free gas diffuses through the matrix to the cleat system [Atkins, 2003].

CBM reservoirs are very variable in thickness and coal properties. Lateral heterogeneity in gas content and cleats permeability is an issue during production period of CBM. Intense well pattern with different completion approach are needed to increase gas production from coal [Atkins, 2003].

Recognizing the main direction of face cleats and butt cleats is the most important factor in designing well pattern in CBM.

Drilling horizontal and multilateral wells are very popular in CBM fields which conclude to have large drainage area in CBM wells [Maricic, 2005].

In order to increase conductivity in CBM reservoirs, most CBM wells are treated by hydraulic fracturing. Hydraulic fractures connected to face cleats network could provide very ideal flow path for desorbed gas. Moreover, due to lateral variation in CBM fields, hydraulic fracturing assists to connect isolated gas-bearing zone to production wells.

The ultimate gas recovery from CBM is highly dependant to maintenance of fracture conductivity performed by hydraulic fracturing [Lehman *et al.*, 1998]. Hydraulic fractures also help to rapid de-watering and pressure decline of CBM reservoirs [McDaniel, 1990].

In this paper the results of gas flow simulations will be presented to show the importance of cleat pattern and the impact of their effective communications for enhanced production. Similarly, the results corresponding to a horizontal well that includes some hydraulic fractures will be presented which demonstrates how production may be enhanced using these strategies. The results show the capabilities of FLUENT for fluid flow simulations in CBM reservoirs.

2. Flow simulations using FLUENT

In this study the flow of gas in cleats is assumed to be laminar, incompressible, isothermal and in a steady-state regime considering a viscous Newtonian fluid [Zimmerman and Bodvarssoni, 1996]. In FLUENT, continuity and momentum equations are solved to determine the fluid flow properties such as pressure drop or velocity magnitude. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was utilised to estimate the pressure. The model geometries were built using Designmodeler, one of the ANSYS software modules. Meshing was also performed using ANSYS mesh facilities. A high density grid were applied to the proximity of the cleats and perforation tunnels to ensure adequate accuracy of the results when it is run in FLUENT. The velocity inlet and pressure outlet, with zero gauge pressure at outlet, were chosen as boundary conditions in all models. All other solid surfaces were defined as wall with no slip velocity boundary condition. The single phase flow of methane gas was considered for the simulation in this work. This, in fact, corresponds to the mid phase of gas production when the dewatering is completed. A velocity of 0.001 m/s was assumed for gas at the inlet and porous media with different permeabilities were assigned to different regions, i.e. wellbore, cleats and coal seam, which controls the gas flow across different sections.

The porous media in FLUENT is defined using two terms of viscous and inertial loss, which are added into the fluid flow equations. The source term including these terms is defined as [FLUENT tutorial, 2001]:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho |v_j| v_j \right). \qquad (1)$$

Here S_i is the source term for the ith (x, y, or z) momentum equation, and D and C are prescribed matrices. This momentum sink contributes to the pressure gradient in the porous cell, creating a pressure drop that is proportional to the fluid velocity in the cell.

For a homogenuous porous media equation 1 simplifies to

$$\frac{\Delta p}{l} = -\left(\frac{\mu}{\alpha} v + C\frac{1}{2}\rho v^2 \right). \qquad (2)$$

This equation calculates the pressure drop per unit length in a porous media with permeability α (or viscous resistance K=1/ α) and inertial resistance C for a fluid with viscosity μ and density ρ flowing at a mean velocity v. Table 1 summarises various parameters used for simulations in FLUENT.

To illustrate the modelling in FLUENT in Figure 2 a simple 2D geometry is shown where an inner formation (rectangular shape with length of 20 cm and width of 6 cm) is surrounded by an outer formation (rectangluar shape with length of 100 cm and width of 20 cm). Water with density of 998.2 kg/m^3 and viscosity of 0.001003 kg/m.s was assumed for this simulation. The model boundaries and interior are also shown in this figure. Mass flow inlet of 0.20 kg/s was considered as inlet boundary, which corresponds to a velocity magnitude of 0.001 m/s at the inlet. Figure 3 shows the static pressure and velocity magnitude contours corresponding to a situation where the inner formation is highly impermeable (K_i=1×10^8 m^{-2}) but the outter formation is highly permeable (K_o=0 m^{-2}). From this figure it is seen that the pressure reduces from inlet to the oulet as expected but the range of pressure is very low (i.e. a pressure drop of approximately 2.67×10^{-3} pa. This is due to the fact that the outer formation with larger area is highly open to fluid flow. The velocity magnitude within the inner formation is significantly reduced due to this formation being impermeable whereas it increases in both sides of the inner formation (up to 1.88×10^{-3} m/s) due to a lesser width for the fluid path.

Table 1: Coal seam reservoir data used for FLUENT simulations

Parameter	Value
Methane:	
Density (kg/m^3)	0.6679
Viscosity (kg/m.s)	1.087×10^{-5}
viscous resistance (m^{-2}):	
Coal seam	1×10^{8}
Face cleats	50
Butt cleats	200
Hydraulic fractures	10
Boundary conditions:	
Interior, porous media	Coal seam, cleats, perforations
Inlet	Velocity inlet, 0.001 m/s
Outlet	Pressure outlet

Figure 4 presents the contours of velocity magnitude corresponding to another three cases with different permeabilities for the two formations. Figure 4(a) shows the results of a case opposite to that of Figure 3, i.e. K_i=0 m^{-2} and $K_o=1\times10^{8}$ (m^{-2}). In this case the velocity, as was expected, increases within the inner formation but its maximum value (4.56×10^{-3} m/s) is larger than that of case showiun in Figure 3. A pressure drop of 50.5 pa was obtained from FLUENT simulation for this case. This large pressure drop, comparing to Figure 3 is due to the fact that in this case the outer formation with larger area open to fluid is highly impermeable and therefore causes a large resistance against fluid flow.

The velocity magnitude shown in Figure 4 (b) corresponds to a situation where both formations have a similar $K_i=K_o=1\times10^{8}$ (m^{-2}), i.e. both formations have very low permeability. A similar velocity profile shown in this figure indicates how both formations are considered as a unit geometry. A pressure drop of 100 pas was obtained from FLUENT simulation. Similar result will be obtained if equation 2 is used to estimate pressure drop for this geometry, assuming an inertial reisstence of zero, i.e. C=0. A larger pressure drop of about twice that of shown in Figure 4 (b) is due to the fact that both formations are very low permeable.

Finally, the results presented in Figure 4 (c) correspond to a situation where both formations are highly permeable, i.e. $K_i=K_o=0$ (m^{-2}). A very low pressure drop of 0.75×10^{-3} pa obtained from FLUENT, i.e. lesser than that of Figure 4 (a) shows how the entire model is conductive to fliud flow.

The results presented in Figures 3 and 4 demonstrate how FLUENT can be used for various fluid flow simulations with formations having different flow properties. Also, the fluid properties can be changed, for example, with particular application to the CBM, methane gas will be used for flow simulations in the rest of this paper.

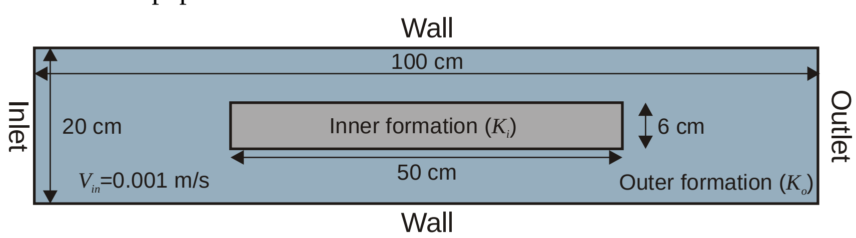


Figure 2: Model geometry used for FLUENT Simulation

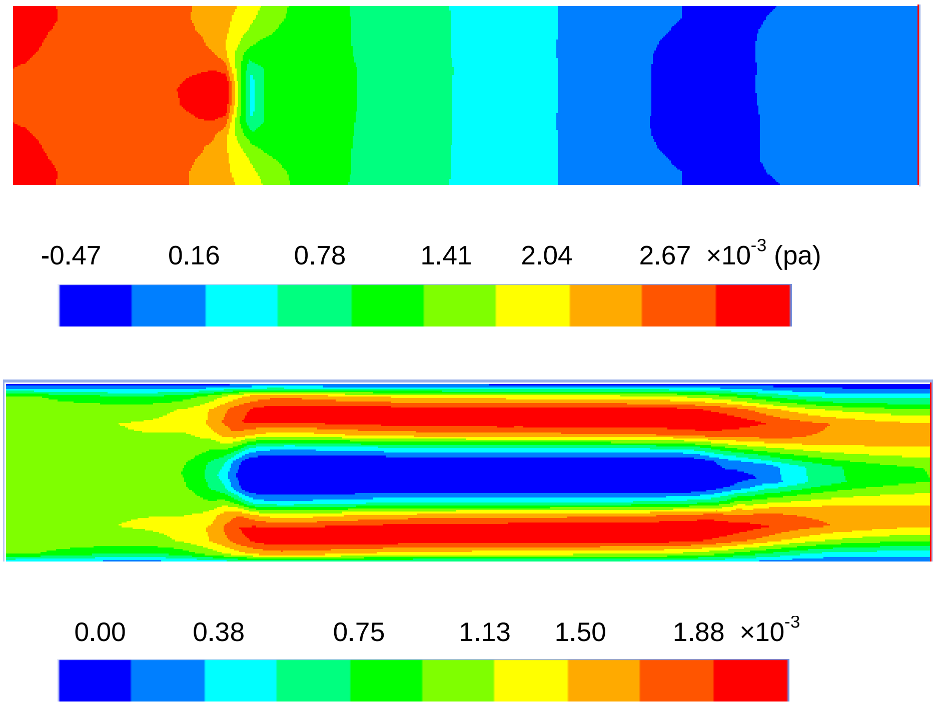


Figure 3: Total pressure (top) and velocity magnitude (bottom) contours corresponding to a porous medium surrounde by a high permeable formation; K_i=1×10^8 (m^{-2}) >>K_o=0 (m^{-2})

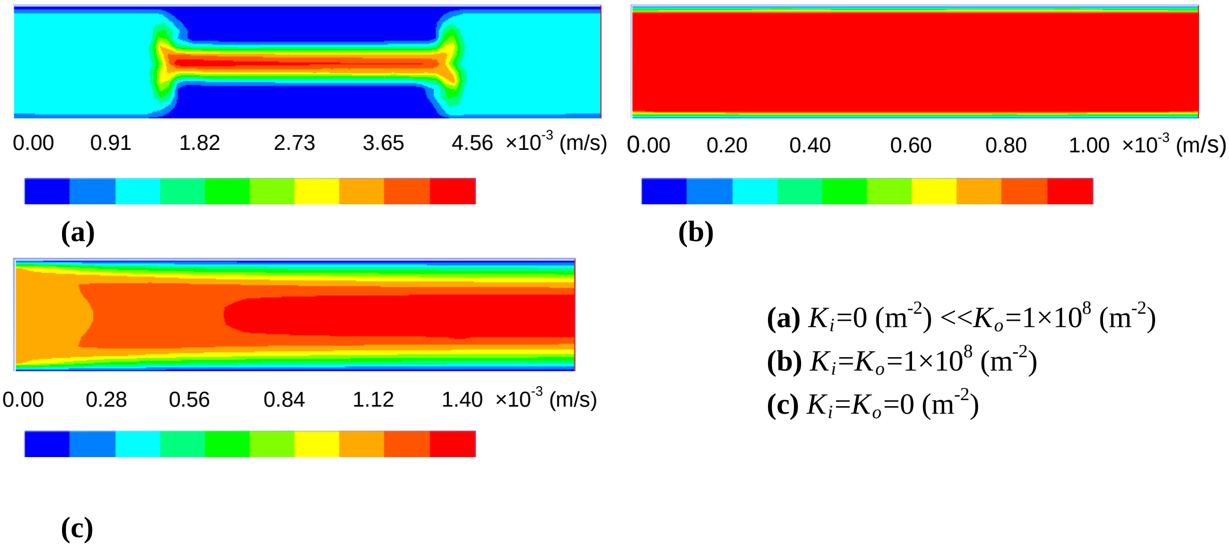


Figure 4: Contours of velocity magnitudes when the two formations have different (a) and similar permeabilities (b and c)

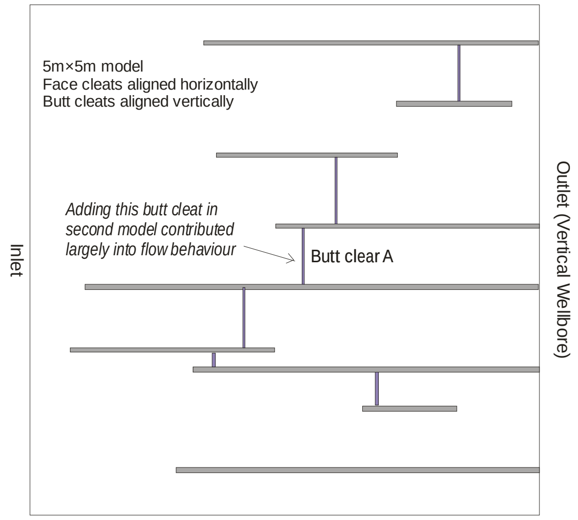
3. Gas flow simulations in a coal seam

In this section we present the results of some simple 2D simulations of gas flow in a coal seam. The objective here is to simply indicate the capabilities of FLUENT in modelling various flow scenarios corresponding to a coal seam. Simple models are presented followed by more complicated cases where horizontal wells with perforations are simulated for flow studies.

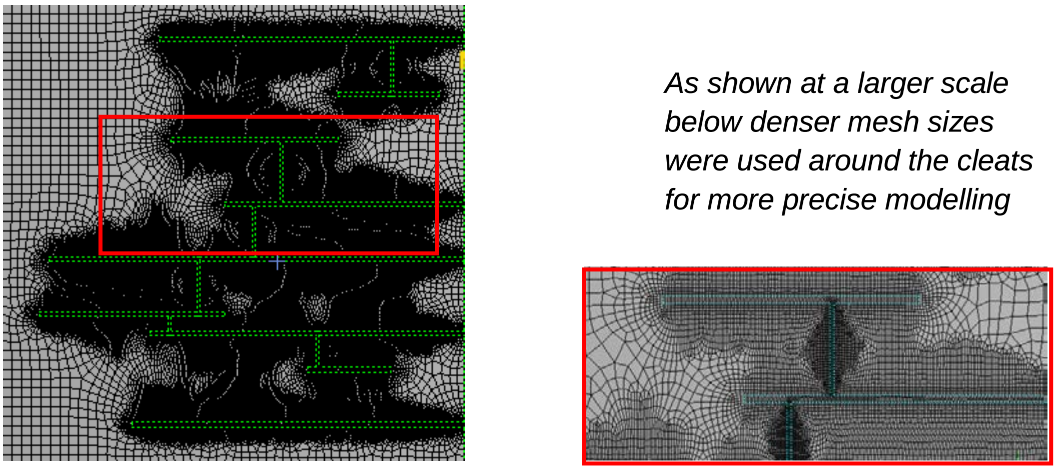
Cleats model

The main path for gas flow in a coal seam is through the face cleats and therefore the characteristics of these natural fractures appear to be very important in terms of production from a CBM reservoir. The cleat density (i.e. number of cleats in a unit volume), the aperture and permeability of cleats are the most important parameters contibuting to different production rate from a coal seam. Assuming mid phase production where dewatering has been already completed and the methane has desorbed from coal and is flowing into cleats we have performed some simulation scenarios to demonastrate the influence of cleats' properties on flow behaviour.

Figure 5 (a) shows a small scale 2D geometry corresponding to a section of a coal seam with a length and width of 5 m, respectively. The left boundary is the model inlet where the gas is travelling towards the right boundary, which is the model outlet corresponding to a vertical wellbore here. Open hole production is only considered here for demonstration purposes. A random pattern of face and butt cleats were generated as is shown in this figure. Butt cleat A was used at the second part of the simulations to indicate the importance of cleats connectivity for production purposes. At this stage a constant aperture of 5 cm and 3 cm were considered for face and butt cleats. respectively. This is while in real situation the cleats' aperture is in the order of milimetre but here using these values found more appropriate for demonstration purposes. As shown in Figure 5 (b) a high density mesh was used in approximity of cleat surfaces in order to obtain accurate estimation of flow properties in these areas.



(a)



(b)

Figure 5: A 2D model used for flow in a coal seam (a) and the meshing generated for FLUENT analysis (b)

Figure 6 shows the static pressure and velocity magnitude contours for geometry shown in Figure 5 after the model was run using FLUENT. The results shown in this figure are for a case where cleat A does not exist in model geometry. The flow of gas towards the wellbore is seen from this figure but the most significant flow concentration is within the area surrounded by a coonected loop of face and butt cleats. This indicates the importance of effective communication between cleats for an enhanced production. A pressure drop of 4.5×10^{-5} pa is obtained from FLUENT (Figure 6, left) between the model inlet and the gas entery into the wellbore.

In Figure 7 the velocity magnitude contours are presented for the case where cleat A is added into model geometry. Although the butt cleats' permeability is very low, the communication path that this cleat creates will result in a different velocity magnitude distribution, as is seen in Figure 7. In this case the flow velocity is larger at both sides of cleat A, opposite to what observed in Figure 6. A smaller pressure drop of less than 0.12×10^{-5} pa was observed for the latter case comparing to Figure 5, which indicates a more effective flow path when cleat A is included in the simulations.

The above results indicate that the connectivity between face cleats is critical for optimised production and according to several simulations it is found to be more improtant than the number of cleats.

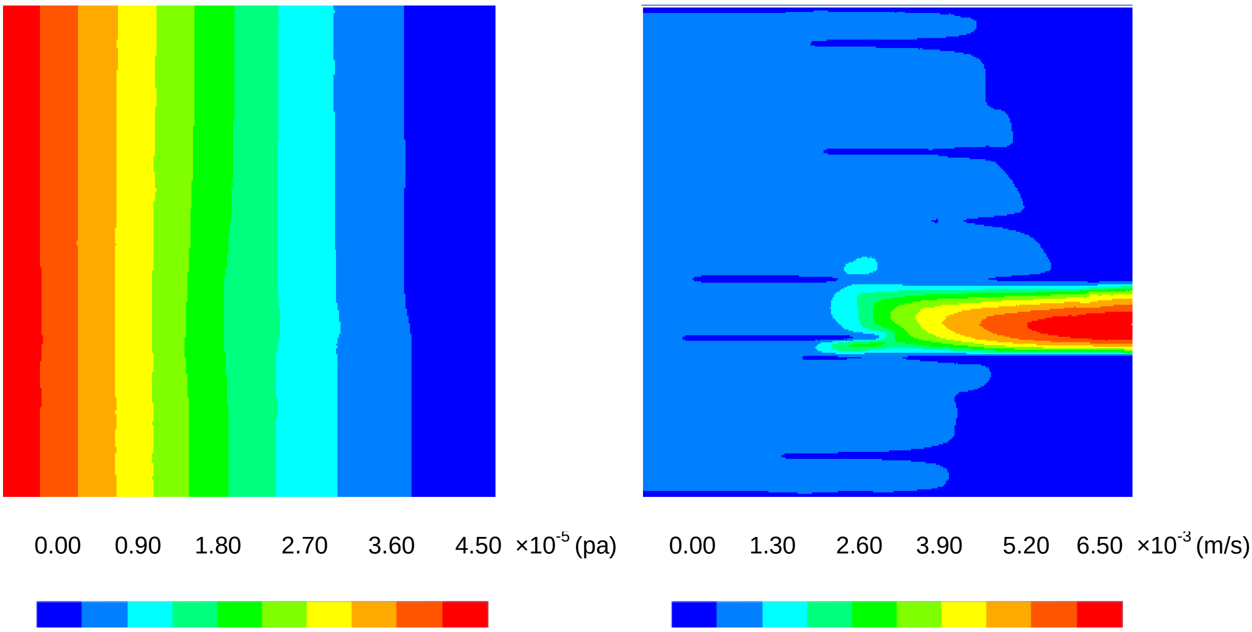


Figure 6: Static pressure (left) and velocity magnitude contours corresponding to model geometry in Figure 5 when butt cleat A does not exist

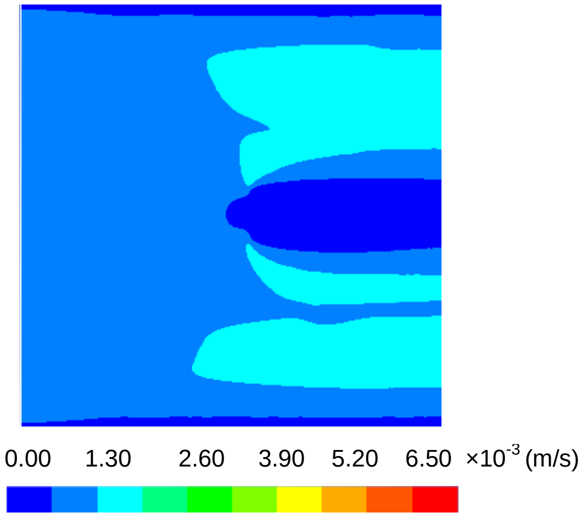


Figure 7: Change in velocity contours when cleat A is added in model geometry in Figure 5

Horizontal drilling model

The discussion of the previous section showed that providing a larger exposure of the coal seam to the wellbore is an effective way for increase production. Therefore horizontal drilling in coal seams appears to be an alternate approach for enhanced production, as in this case the wellbore would be expected to intersect larger number of cleats and produces a more effective path for gas to enter the wellbore. To demonstrate this, in Figure 8 (left) a horizontal wellbore added into the model geometry of Figure 5 is shown. The wellbore diameter in this case is 300 mm. To force the gas to flow radially towards the wellbore the model inlet and outlet were changed: here the gas enters from the upper and lower boundaries and exit at the vertical boundary of the horizontal wellbore at the right, as depicted in Figure 8 (a). Keeping all parameters similar to Figure 7 the model was run and the velocity magnitude contours are shown in Figure 8 (right). This figure shows how the flow is converged into the horizontal wellbore with a larger exposure, which ultimately increases production.

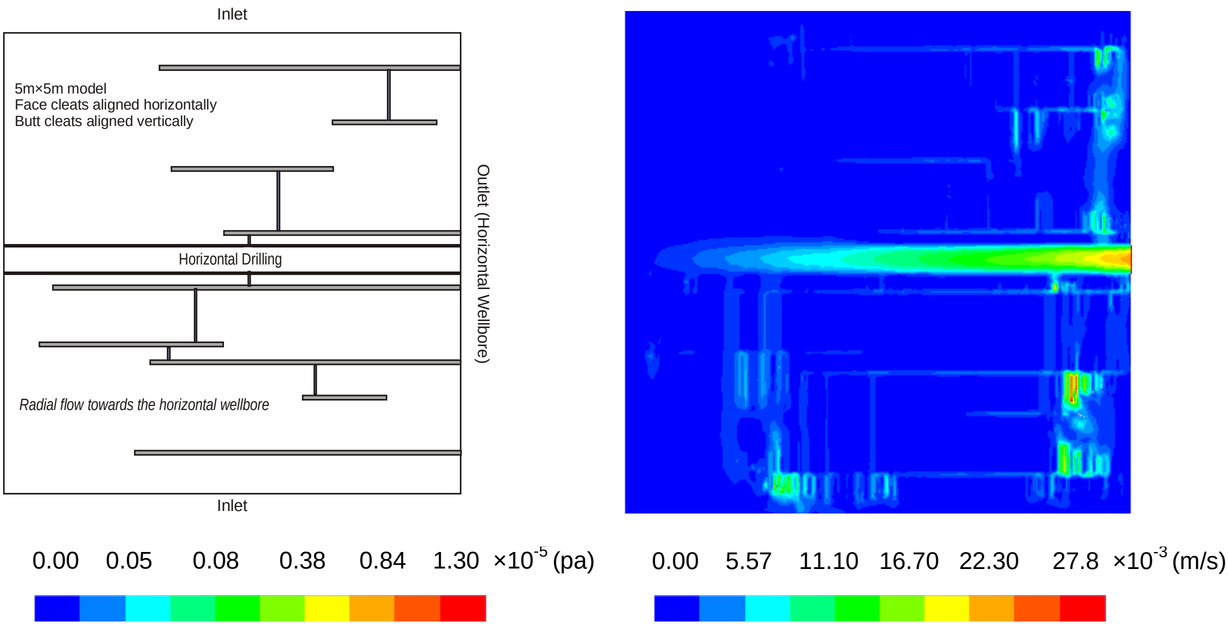


Figure 8: Static pressure (left) and velocity magnitudes corresponding to a horizontal well drilled in a coal seam

Hydraulic fracturing

An alternative approach for enhanced production in CBMs is the hydraulic fracturing. An induced fracture, if operated effectively, would act as a communication path between cleats and can enhance production by a large amount. From a geomechanics point of view a hydraulic fracture propagates along the direction of maximum stress in the field. At lower depths the vertical stress is likely to be the least principal stress in the field with one of the horizontal stresses being the maximum stress. This state of stress is known as strike-slip stress regime which results in a horizontal hydraulic fracture to be propagated perpendicular to the least stress direction (i.e. vertical). An opposite scenario is a normal stress regime where the vertical stress is the largest principal stress in the field: this occurs usually at larger depths where overburden weight is increases. As coal seams are located in relatively low depths, both stress regimes may be observed when drilling in a coal seam.

The face cleats are usually aligned in the direction of maximum stress in the field and therefore, for example, in a horizontal well shown in Figure 8 performing sequence of hydraulic fracturing would be more effective if normal stress regime is dominant in the field, as in this case induced fractures propagate vertically and connect larger number of face cleats.

In Figure 9 (left) four hydraulic fractures operated at an average distance of 1 m from each other from the horizontal wellbore are shown in the model geometry. This geometry corresponds to a normal stress regime. A fracture width of 70 mm and length of 1 m was assumed for simulation purposes. This is while the fracture width in real operation is in the order of few milimitres. The results of FLUENT simulations corresponding to this geometry is shown in Figure 9 (right). As explained above by intersecting face cleats these fractures will provide a more effective route for the gas to flow into the wellbore. Larger flow convergence towards the hydraulic fractures indicates the importance of stimulations for enhanced production in coal seams.

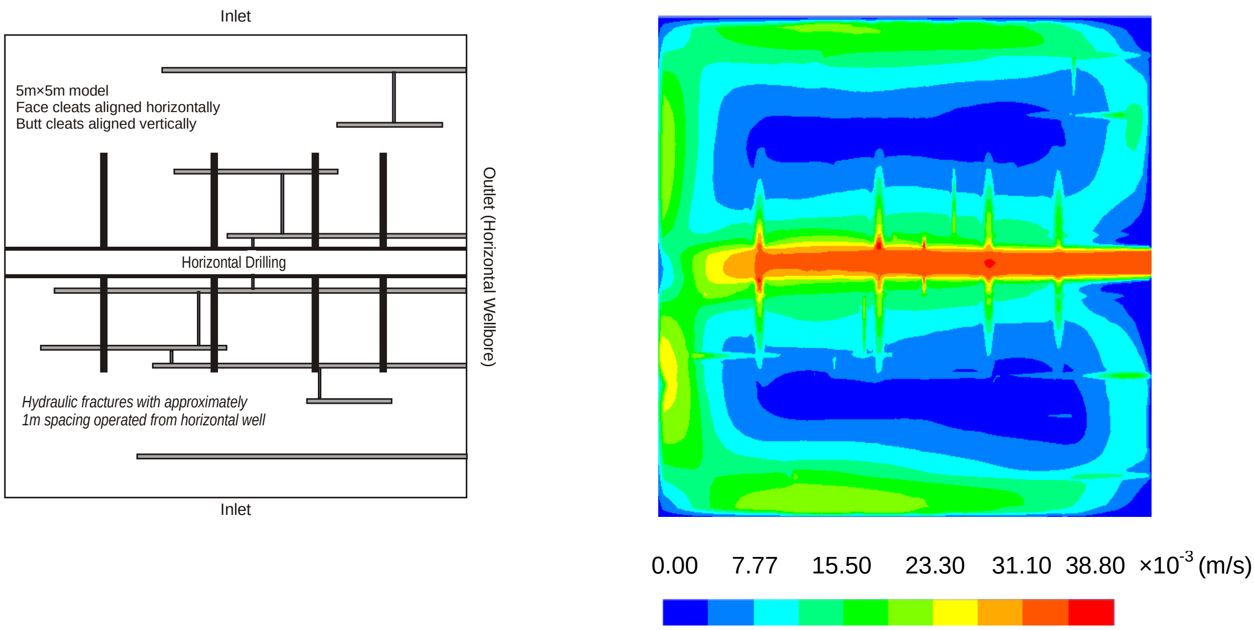


Figure 9: Hydraulic fractures provide a more effective flow path for gas migration to wellbore. Model geometry (left) and contours of velocity magnitudes

4. Conclusions

In this paper the results of FLUENT flow simulations were presented for some simple scenarios in a coal seam. The results showed how FLUENT is capable to consider different fluid properties and well geometries as well as formations with different fluid conductivities. The results indicated that communication between cleats is the most important in production from CBMs. Also, through simple models it was shown how drilling horizontal wells and hydraulic fracturing may help in improved production by intersecting larger number of cleats and providing a larger exposure to the coal seam.

Further simulation is ongoing to study the effect of other geometries including perforations and fracture geometry. Also, performing 3D simulations is the next step in this study.

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