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COMPOSITIONAL SIMULATION OF COALBED METHANE RESERVOIRS

Summary. Numerical models used for modeling of coalbed methane production are briefly presented in the paper. The numerical example using compositional approach has been presented. The results of the numerical simulations are discussed for fictitious coal seam to show degassing efficiency depending on coal properties. It was shown that both instant and time depended sorption can be simulated using different values of the diffusion coefficient. The influence of ventilation on the composition of the produced gas has also been simulated.

MODELOWANIE SYMULACYJNE EKSPLOATACJI METANU Z POKŁADU WĘGLA

Streszczenie. W pracy przedstawiono dwa alternatywne modele symulacyjne, umożliwiające modelowanie zjawisk fizycznych zachodzących w pokładzie węgla nasyconym metanem. Podano przykłady obliczeniowe procesu eksploatacji metanu z pokładu węgla z uwzględnieniem modelowania zmian składu gazu wynikających z wprowadzania powietrza wentylacyjnego. Wskazano wpływ współczynnika dyfuzji metanu w węglu na szybkość i efektywność odgazowania pokładu.

1. Introduction

Providing safety of work in hard coal mines during coal exploitation in high methane hazard conditions requires employing various methods, as well as technical and prevention measures, with focus on efficient methane removal. Methane hazard has influence on the safety of work. It may also limit the level of coal extraction, thus influencing the economic effect of the mine. On the other hand, coalbed methane started to grow in economic significance as a valuable source of energy (Stopa et al., 2008). This is especially important in Poland, where the documented coalbed methane resources are comparable with natural gas resources in conventional fields. It should be remembered, however, that the efficiency of coalbed methane is much lower than that of natural gas (Table 1).

Table 1

Coalbed methane vs. conventional natural gas resources in Poland, 1997 (Nawrat et al., 2008)

	Coalbed methane, mld m3	Natural gas mld m3
Resources	150	151
Production	0.289	4.2
Ventilation to the atmosphere	0.581	-

Designing and methane removal processes in coal mines have been mainly based on practical experience, being one of the causes of low efficiency of methane removal. The evaluation and monitoring of methane removal processes, especially in time, also create significant problems. The applied design methods are to a great extent subjective, so the coalbed methane removal processes cannot be optimized (Nawrat et al., 2008).

Problems related with designing and optimization of coal beds can be solved with the use of reservoir engineering methods, mainly computer simulations, as in the case of conventional natural gas fields. Owing to specific coal properties, special mathematical models and simulation programs have to be used.

2. Mathematical models of gas flow in coal beds

Coal bed, being a flow system, is a double porosity and double permeability system (King, Ertekin, 1988). Two hydraulic systems can be distinguished there: porous coal matrix and a network of cracks, fractures or larger pores which are either interconnected or discontinuous dead-ends. In a coal bed methane model the pore volume of the fractures has a different interpretation than for an ordinary dual porosity models; it gives the non-coal volume of the simulation cell. If the coefficient of "fracture" porosity equals to ϕ, then the coal substance volume in a geometrical unit of bed is $1-\phi$. Thus defined coefficient of fracture porosity may vary in a vast range, so for the exploited beds it may have considerably higher values than for undisturbed coal seams. The mass is mainly transported by a system of fractures, where Darcy's law is operational; matrix, which can be related with coal substance, has a considerable storing capacity, being a "source of mass" for the system of fractures. Initially, in the natural state, these systems are in the state of hydrodynamic equilibrium under a pressure exerted by the overburden. Gas appears in the free and adsorbed form in the matrix; however bigger gas resources are usually accumulated in the matrix. Its production results in the lowering of pressure in fractures, causing gas desorption and its flow from the matrix to the fractures. Owing to high permeability of the fracture system, the state of equilibrium is shaken and the pressure inside of the matrix blocks may be higher than in the fractures. Coal beds are frequently watered therefore gas flow may be accompanied by mine's brines. Therefore, theory of relative permeability, widely applied in the oil and natural gas engineering, should be accounted for in the mathematical model (Stopa, 1996).

In a majority of cases a mathematical model describing a two-phase flow in coal, the so-called Warren-Root model is operational (Guo et.al., 2003; Seidle, 1993, Remner, et al., 1986). Gas is treated as a homogeneous fluid, the properties of which depend only on pressure. In this model a coal bed is characterized by two porosity systems, i.e. system of fractures and matrix. The first of them is water and gas permeable, and the flow is ruled by the Darcy's filtration law. It is assumed that in the second case no macroscopic flow takes place. Only mass exchange between matrix and the system of fractures may take place. It is, however, frequently assumed that sorption equilibrium exists between the system of fractures and the matrix. This state of equilibrium is described by a relation between the quantity of adsorbed and free gas depending on pressure, the so-called Langmuir isotherm. A more advanced approach has been assumed in a mathematical model where the coalbed gas may be a mixture of, e.g. methane, nitrogen, oxygen etc. as it is the case for compositional models known from petroleum engineering. This enables one to model the influence of bed ventilation and, e.g. evaluate the outburst hazard. Simplified example of such modeling for fictitious coal bed is presented in the paper. Calculations were made with the use of a professional composition simulator Schlumberger ECLIPSE300 (for details see the address in References). The modelling was aimed at analyzing the influence of intensity of time depended sorption on degassing of the bed. In the state of equilibrium the sorption capacity of i-th component is described by an equation, being a generalized form of Langmuir isotherm (ECLIPSE Reference Manual, 2007):

$$V_{E,i}(p, y_1, ..., y_{Nc}) = V_i \frac{y_i \frac{p}{P_i}}{1 + \sum_{j=1}^{Nc} y_j \frac{p}{P_j}} \tag{1}$$

where:

$V_{E,i}$ – volume of i-th component absorbed in a coal unit at equilibrium, sm^3/kg

V_i = Langmuir volume constant for i-th component, m^3 (maximum sorption capacity)

P_i = Langmuir pressure constant for i-th component, Pa

yi = molecular share of i-th component in the gaseous phase

p = pressure, Pa

The multicomponent adsorption capacity can be more conveniently expressed in moles per unit of coal mass, using the ideal gas law (ECLIPSE Reference Manual, 2007):

$$L_i(p, y_1, ..., y_{Nc}) = \frac{p_{sc}}{R \cdot T_{sc}} \cdot V_{E,i}(p, y_1, ..., y_{Nc}) \tag{2}$$

where:

P_{sc} = normal pressure

R = universal gas constant

T_{sc} = normal temperature

If the pressure in fractures is changed, then diffusive exchange of mass between fractures and matrix takes place. The gas flowing between the matrix and the fractures per unit of coal volume is described by the following equation (ECLIPSE Reference Manual, 2007):

$$F_i = \sigma \cdot D_{c,i} \cdot S_g \cdot RF_i \cdot (m_i - \rho_c L_i), \ [mole/(m^3 s)] \tag{3}$$

where:

L_i = sorption capacity of coal for i-th component in the state of equilibrium, mole/kg (in moles per kg of coal mass)

m_i = mole concentration of i-th component adsorbed in the matrix, $[mole/m^3]$, (per unit of coal volume)

σ = coefficient of mass exchange between fractures and matrix, $[m^{-2}]$, depending on characteristic size of the matrix block

ρ_c = density of coal, $[kg/m^3]$

$D_{c,i}$ = coefficient of diffusion of i-th component in coal, $[m^2/s]$

RF_i = coefficient of re-adsorption for i-th component, assumed $RF_i = 1$

S_g = saturation with gas, for desorption $S_g = 1$

In the above equation $\rho_c L_i$ represents average mole density of adsorption of i-th component in the state of sorption equilibrium calculated for a unit of coal volume. In literature a coefficient of $\tau_i = (\sigma \cdot D_{c,i})^{-1}$, known as sorption time constant, is frequently used. It is a measure of how quickly a state of equilibrium between the matrix and fractures is attained.

This approach enables modelling of a number of phenomena, e.g. variability of gas composition, preferred sorption of certain components, e.g. carbon dioxide vs. methane, or delaying desorption of methane from the matrix in relation to the change of pressure in fractures.

3. Example of numerical modelling of sorption in a coal bed

To analyze the influence of sorption on the rate of gaseous exchange between coal matrix and the system of fractures, a composite numerical model consisting of three elements: N2, O2 and CH4, and accounting for double porosity of the bed, has been worked out. The model assumed impermeable coal matrix and permeable fractures (ca. 500 mD). Two wells were used in the model: the production well and air injection well (representing a ventilation system).

The basic parameters of the model are listed in Table 2.

Table 2

Basic parameters of the model

Magnitude of the model	50m x 50m x 18m
Permeability of fractures	500 mD
Porosity of fractures	0.1 %
Initial pressure in the bed	20 bar
Number of wells	2
Langmuir pressure constant	46.885 bar
Langmuir volume constant	0.01180736 nm^3/kg
Exploitation well control	bottom-hole pressure 0.9 bar
Injection well control	bottom-hole pressure 1.1 bar

Calculations were performed for various diffusion coefficients, and for the simplicity sake, identical for all gas components:

Variant 1 – $D_{c,i} = 1 \cdot 10^{-10}$ m²/day;

Variant 2 – $D_{c,i} = 1 \cdot 10^{-4}$ m²/day;

Variant 3 – $D_{c,i} = 1 \cdot 10^{-3}$ m²/day.

Identical Langmuir isotherm coefficients were assumed for all components as initially only methane is presented in the bed, whereas air is introduced and removed at a pressure close to atmospheric. This causes that in this particular case the air sorption/desorption processes are negligible and the model is practically insensitive to the changes of Langmuir numbers for these components. Chemical reactions between coal and air (and possible temperature effects) are neglected.

Changes of gas quantity in the matrix and the system of fractures during modeled exploitation are presented in Fig 1.

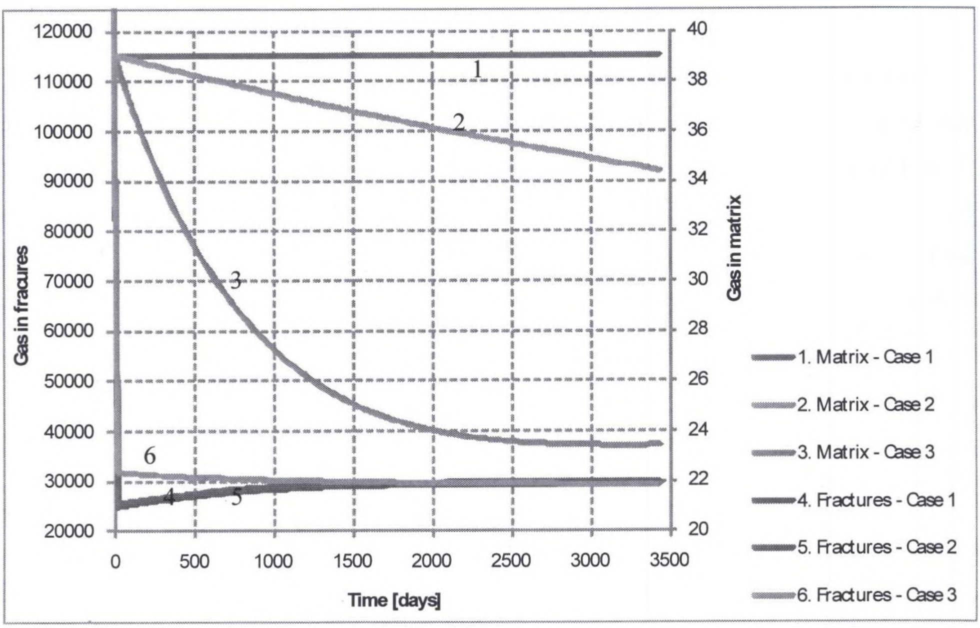

Fig. 1. Change of gas quantity in matrix and fractures [m^3]
Rys. 1. Zmiany objętości gazu w matrycy i szczelinach fractures [m^3]

In variant 1 at very low diffusion coefficient, no gaseous exchange is observed between matrix and the fractures. The produced methane mostly comes from fractures. For the diffision coefficient equal to $1 \cdot 10^{-4}$ m^2/day, gas starts to gradually flow from matrix to the fractures, where after prior rapid drop of methane content, caused by exploitation, its content slightly increases. This means that the gas outflow from the matrix is slightly bigger than the yield of the production well. In variant 3, for diffusion coefficient of $1 \cdot 10^{-3}$ m^2/day the drop of methane content in the matrix is notable. Analogous to variant 2, methane content in the fractures rapidly drops at the initial stage of production, when the bed is degassed, to slightly increase later on. As in all variants the production was controlled by maintaining constant bottom-hole pressure; considerable degassing of the matrix is a proof of increased gas efficiency in this variant (Fig. 2). Methane yield is presented in Fig. 3.

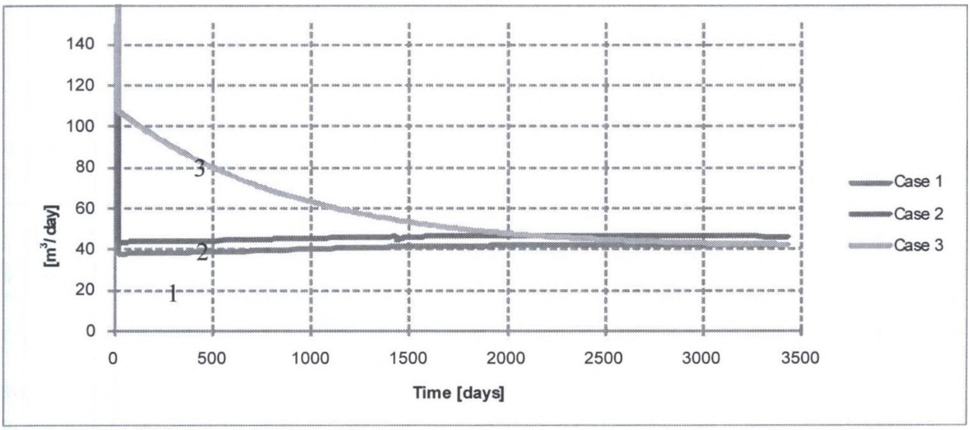

Fig. 2. Gas yield from production well
Rys. 2. Uzysk gazu z otworu eksploatacyjnego

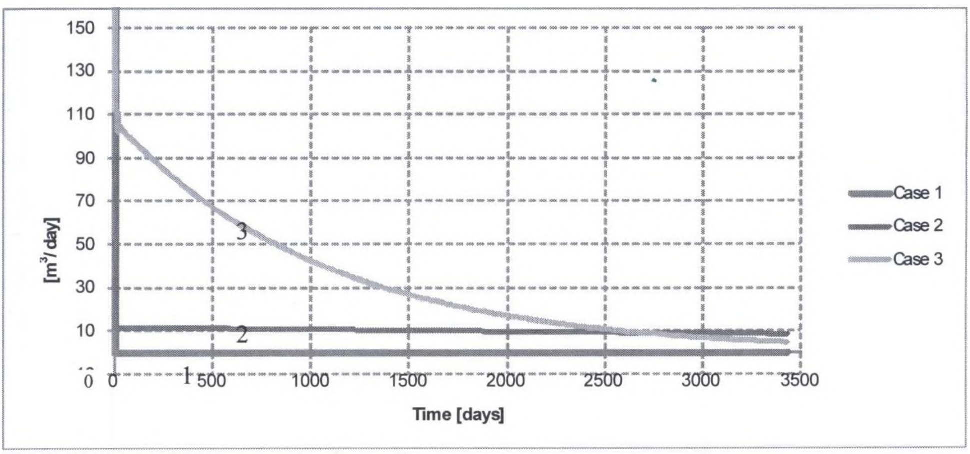

Fig. 3. Methane yield from production well
Rys. 3. Uzysk metanu z otworu eksploatacyjnego

4. Conclusions

The gas flow between coal matrix and a system of fractures strongly depends on the physical properties of coal. The diffusion coefficient, controlling the time depended desorption, plays an important role in this process. When the coal bed is degassed, at low diffusion values, the time of gaining sorption equilibrium may be very long, and consequently, gas may be removed only from the system of fractures, where the pressure will considerably lower. The methane concentration in matrix may remain high and at higher pressure. This situation causes long-term methane emission, creating outburst hazard during mining operations.

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