

Prediction of Coalbed Methane Well Production by Analytical Method

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Abstract: The motive of the study is to propose a water-gas two-phase flow model to depict the characteristics of Coalbed Methane (CBM) transporting in the unsaturated coalbed and predict the production of CBM well. The proposed model is established based on Buckley-Leverett equation. The calculating equations of daily gas and water production of CBM well are derived from the proposed model. A program is achieved based on the equations and an actual CBM well is simulated as an example. The simulated results are verified by the actual site monitoring values. Moreover, the effects of permeability, porosity, well control radius, coalbed thickness and coal-rock matrix radius on the daily gas production and cumulative gas production of CBM well are studied. The comprehensive results address that the equations of daily gas production and cumulative gas production are good agreement with the monitoring values. Daily gas production increases with increasing permeability. Greater porosity means higher initial and stable daily gas production. Appropriate increase of the well control radius can improve the initial and stable daily gas production. However, when the well control radius reaches a critical value, it has no effect on the daily gas production. The initial gas production increases greatly with increasing coalbed thickness and matrix radius.

Keywords: Buckley-Leverett equation, coalbed methane, production prediction, sensitivity analysis, water-gas two-phase flow model

INTRODUCTION

Coalbed methane (CBM) is one of the fatal factors threatening the safety of coal mining. The coal mining wells with high content CBM are about 49.8% of the total coal mining wells in China, which becomes a critical factor restricting the safe exploitation of coal mining. At the same time, CBM is considered as important as the natural gas to ensure the energy sources safety of China (Wang *et al.*, 2010a, 2011a). Therefore, the exploitation of CBM has become the prerequisite for coal mining in China. In the exploitation process of CBM, plenty of confined water is often drawn out of coalbed to form spaces for the desorptions and transitions of CBM. The gas-water two-phase flow problem is existed in the process. At the same time, coal is a special medium made up of coal-rock matrix and seam, which are the lodging place and main migrating pathway of CBM, respectively (Wang *et al.*, 2010c; Yan *et al.*, 2010a, 2010b; Ren *et al.*, 2012). Moreover, the coal-rock matrix shows a strong anisotropy and the permeability of the face seam and butt seam differs from each other significantly. All above

reasons cause that the production prediction of CBM well become very complex and challengeable. However, accurately predicting the production of CBM well is a key factor to determine whether the hydraulic fracturing or injection of miscible gas is necessary. Many scholars have studied this problem, e.g., (McKee and Bumb, 1987; McKee *et al.*, 1988) assumed the CBM transmitting from the micro-porosity into macro-porosity of coal-rock matrix instantly and established the calculation model of CBM well production. As the neglect of CBM seepage characteristic in the micro-porosity, the production obtained by the model tended to be higher than the monitoring data. Sawyer *et al.* (1990) and Paul and Sawyer (1990) classified the flow of CBM and water in the coalbed as steady and unsteady flow and built up corresponding mathematic models. They thought the migration of CBM and water in the micro-porosity obeyed the nonlinear flow law while the migration in the seam and fracture obeyed Darcy's law. Although the mathematic model could precisely describe the migrating characteristics of CBM and water, the solutions were very complex and took too much time. Meanwhile,

some scholars (Seidle and Arri, 1990; Arri *et al.*, 1992) simplified the coal-rock matrix and CBM as oil and volatile gas, respectively. The black-oil model was introduced into the prediction of CBM well production and equations were also derived. Some useful conclusions were achieved. However, this model was also with some limitations for ignoring the influences of porosity, saturation and thickness of coalbed.

Therefore, the aims of the study are to establish a new model according to the migrating characteristics of two-phase flow in the unsaturated coalbed, which can predict the characteristics of CBM transporting in the unsaturated coalbed and CBM well production. Corresponding calculating formulas of CBM well production are derived based on Buckley-Leverett equation. Galerkin method and implicit difference method are used to solve the formulas. A calculation program is developed accordingly. Moreover, a field CBM well is simulated as an example to validate the accuracy and precision of the calculating formulas. The influences of permeability, porosity, well control radius, coalbed thickness and coal-rock matrix radius on the production of CBM well are studied.

MATHEMATICAL MODEL

Mathematical model of two-phase flow in unsaturated coalbed: In the exploitation of CBM, the confined water in coalbed will be excluded firstly to form certain spaces, which means the coalbed is in the unsaturated state. Then, CBM turns into free gas by desorption and stores in the spaces. Free gas flows by the micro-cracks of coal-rock matrix and ultimately into the production well together with water (Fig. 1). Therefore, the migration of CBM in unsaturated coalbed is a typical water-gas two-phase flow problem (Liu *et al.*, 2011; Jiang *et al.*, 2011). In the study, the impacts of coalbed characteristic parameters on the migration and production of CBM are mainly studied, while the influence of CBM desorption is not considered. Therefore, the time of CBM desorption is assumed as 0 in the whole calculation.

Two assumptions are used in the model, namely,

- The mass exchange does not occur between CBM and water
- CBM is not soluble in water

CBM and water flow into the fracture system of coal-rock under the pressure gradient, which can be serviced as the source. While the CBM production well is serviced as the sink. Then, the fluid flow equations between the source and sink can be obtained by using two-phase flow Buckley-Leverett equation (Siddiqui *et al.*, 1996; Xiong *et al.*, 2007), expressed as follows:

$$-\nabla \cdot (\rho_g v_g) + q_{yg} - q_{hg} - \frac{\partial(\rho_g \phi S_g)}{\partial t} = 0 \tag{1}$$

$$-\nabla \cdot (\rho_w v_w) + q_{yw} - q_{hw} - \frac{\partial(\rho_w \phi S_w)}{\partial t} = 0 \tag{2}$$

where, ∇ is the Hamilton operator; q_{yg} , q_{yw} are the deliverability of gas and water respectively in the coal-rock matrix fracture and pore system, m^3/d ; q_{hg} , q_{hw} are the productions of gas and water in CBM well, respectively, m^3/d ; ρ_g , ρ_w are the densities of CBM and water, kg/m^3 ; ϕ is the porosity of coal-rock; S_g , S_w are the saturations of CBM and water in the fracture system.

Under the effects of gravity, the velocities of CBM and water can be obtained respectively as below:

$$v_g = -\frac{k_o k_{rg}}{\mu_g} \nabla (p_g - \rho_g g H) \tag{3}$$

$$v_w = -\frac{k_o k_{rw}}{\mu_w} \nabla (p_w - \rho_w g H) \tag{4}$$

where, k_o is the absolute permeability of coalbed at the initial state, m^2 ; g is the acceleration of gravity, m/s^2 ; H is the buried depth of coalbed, m ; μ_g , μ_w are the viscosities of CBM and water in the fracture system, k_{rg} , k_{rw} are

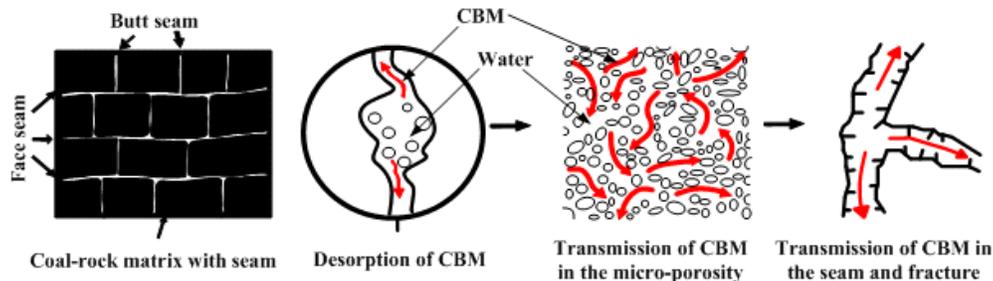


Fig. 1: Schematic diagram of CBM desorption and transmission in the coal-rock matrix

the relative permeability of CBM and water in fracture system; p_g, p_w are the absolute pressure of CBM and water in fracture system, MPa.

By substituting (3) and (4) into (1) and (2), the flow differential equations of gas and water in unsaturated coalbed can be obtained:

$$\frac{\partial}{\partial x} \left[\frac{\rho_g k_{ox} k_{rg}}{\mu_g} \frac{\partial}{\partial x} (p_g - \rho_g gH) \right] + \frac{\partial}{\partial y} \left[\frac{\rho_g k_{oy} k_{rg}}{\mu_g} \frac{\partial}{\partial y} (p_g - \rho_g gH) \right] + \frac{\partial}{\partial z} \left[\frac{\rho_g k_{oz} k_{rg}}{\mu_g} \frac{\partial}{\partial z} (p_g - \rho_g gH) \right] + q_{yg} - q_{hg} - \frac{\partial (\rho_g \phi S_g)}{\partial t} = 0 \quad (5)$$

$$\frac{\partial}{\partial x} \left[\frac{\rho_w k_{ox} k_{rw}}{\mu_w} \frac{\partial}{\partial x} (p_w - \rho_w gH) \right] + \frac{\partial}{\partial y} \left[\frac{\rho_w k_{oy} k_{rw}}{\mu_w} \frac{\partial}{\partial y} (p_w - \rho_w gH) \right] + \frac{\partial}{\partial z} \left[\frac{\rho_w k_{oz} k_{rw}}{\mu_w} \frac{\partial}{\partial z} (p_w - \rho_w gH) \right] + q_{yw} - q_{hw} - \frac{\partial (\rho_w \phi S_w)}{\partial t} = 0 \quad (6)$$

(5) and (6) are the two-phase flow equations of CBM and water in unsaturated coalbed based on Buckley-Leverett formulas, which are implicit equations. Numerical method is recommended in the solution. The classic Galerkin eight-node finite element method and alternating direction implicit difference method (Lahivaara and Huttunen, 2011; Allaneau and Jameson, 2011) are adopted in the study, which can ensure the speed and accuracy of the solutions. Corresponding boundary and initial condition equations are necessary to predict the production of a field CBM well.

Initial conditions and auxiliary equations: At the beginning of CBM exploitation, the pressure of confined water, water saturation and CBM saturation are:

$$P|_{t=0} = P_0 \quad (7)$$

$$S_w|_{t=0} = S_{w0} \quad (8)$$

$$C|_{t=0} = C_{g0} = \frac{P_0 \phi M}{\rho_g TZR} + \frac{P_0 \rho_c V_L}{P_c + P_L} \quad (9)$$

where, $S_g + S_w = 1$; p_0 is the initial pressure of confined water in coalbed fracture system, MPa; S_{w0} is the initial saturation of water; C_{g0} is the initial concentration of CBM, kg/m^3 ; M is the ideal gas molar mass, kg/mol ; T is the temperature of coalbed, K ; Z is the gas compressible factor; R is the gas constant, $\text{J}/(\text{mol}\cdot\text{K})$; ρ_c is the density of coal-rock, kg/m^3 ; V_L is the Langmuir volume constant, m^3/m^3 ; P_L is the Langmuir pressure constant, MPa; p_c is the gas-water capillary pressure, MPa.

Boundary conditions:

Outer boundary condition: Outer boundaries of calculation area with constant pressure in the whole numerical simulation are commonly known as the first

boundary condition. Then, the pressure at the outer boundary $\Xi 1$ can be obtained by (10):

$$P(x, y, z, t)|_{\Xi 1} = P_a(x, y, z, t)(t > 0) \quad (10)$$

Outer boundaries of calculation area with constant flow rate in the whole numerical simulation are commonly known as the second boundary condition. The boundaries are considered as closed boundary with no fluid through. The pressure at the outer boundary $\Xi 2$ can be expressed as:

$$\frac{\partial P(x, y, z, t)}{\partial n}|_{\Xi 2} = 0(t > 0) \quad (11)$$

$$C|_{R=R_c} = \frac{P_f \phi M}{\rho_g TZR} + \frac{P_f V_L \rho_c}{P_f + P_L} \quad (12)$$

where, $p(x, y, z, t)$ is the fluid pressure function; $\frac{\partial P}{\partial n}|_{\Xi 2}$ is the pressure derivative of outward normal at boundary $\Xi 2$; p_f is the initial fluid pressure, MPa; R_c is the well control radius, m. In the production prediction of an actual CBM well, the first and second boundary conditions are recommended at the initial and late stages of the numerical simulation, respectively.

Inner boundary condition: When the diameter and length of CBM well are given, the flow pressure of wellbore at bottom is a constant, expressed as:

$$P(0, 0, 0, t) = P_u(R_c, R_l)(t > 0) \quad (13)$$

$$C \Big|_{\substack{x=0 \\ y=0 \\ z=0}} = \frac{P_u(R_z, R_l) M}{\rho_g TZR} \quad (14)$$

where, P_u is the flow pressure of wellbore at bottom, MPa; R_l is the length of wellbore, m.

According to the initial conditions and boundary conditions, the iterated initial values of daily gas production and daily water production in CBM well can be achieved as follows:

$$q'_{hg} = \frac{2\pi f k_{rg} kh}{\mu_g B_g \left(\ln \frac{R_m}{R_w} \right)} (p_g - p_{fw}) \quad (15)$$

$$q'_{hw} = \frac{2\pi f k_{rw} kh}{\mu_w B_w \left(\ln \frac{R_m}{R_w} \right)} (p_w - p_{fw}) \quad (16)$$

where, q'_{hg} , q'_{hw} are the iterated initial values of daily gas and water production in CBM well, m^3/d ; β is the geometric constant; k is the permeability of coalbed, m^2 ; h is the thickness of coalbed, m ; p_{fw} is the flow pressure at hole bottom, MPa; B_g , B_w are the gas and water volume factors respectively; R_m is the matrix radius of coal-rock, m ; R_w is wellbore radius, m .

Based on the above equations and specific parameters, the production of a field CBM well can be predicted. The effects of different factors on the production of CBM well can be also given based on the calculating results. Moreover, the quantitative influence laws of each factor are obtained accordingly.

RESULTS AND DISCUSSION

In order to validate the accuracy and precision of the proposed model, a calculation program is developed by C++ computer language. A field CBM well in Qinshui basin of China is simulated as an example. The parameters used in the calculations are shown in Table 1. The results and monitoring data are shown in Fig. 2.

Validation: Figure 2 shows the comparisons of numerical results and monitoring data, indicating the numerical results agree well with monitoring data. The average error is about 7%, which can satisfy the accuracy requirements of actual engineering problems. At the same time, we can see the monitoring daily gas production of CBM well increases firstly and then decreases, while the numerical results decrease with time in the whole process. It is mainly because that desorption of CBM from the coal matrix takes some time for actual condition, while the time of CBM desorption is considered as zero in the numerical simulation. Although the error at the beginning is relative large, the average error is still small, showing the proposed model with a high precision.

Analysis of influencing factors: In order to get the influences of coalbed permeability, porosity, well control radius, coalbed thickness and coal-rock matrix radius on daily gas production and cumulative production of CBM well, different values of the factors are assigned. The calculating results are shown in Fig. 3 to 8.

Permeability: Figure 3 presents the relation between daily gas production of CBM well and time under different permeability conditions. As shown in Fig. 3, the

Coalbed thickness/m	6.30	Coalbed temperature/°C	34.30
Coalbed permeability/mD	1.50	Confined water pressure/MPa	3.36
Coal density/(kg/m ³)	1420.00	Coalbed porosity	0.04
Well bore diameter/mm	139.70	Well bore length/m	103.00
Matrix radius/m	0.22	Well control radius/m	120.00
Langmuir pressure/MPa	3.04	Langmuir volume/(m ³ /m ³)	43.95

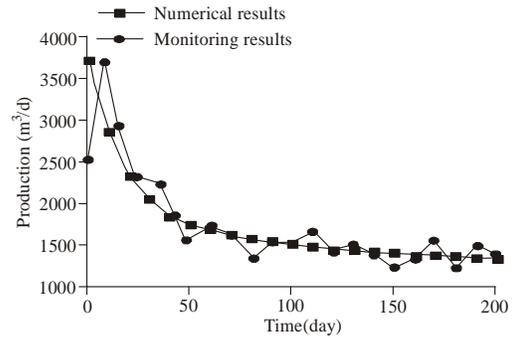


Fig. 2: Relation between daily gas production of CBM well and time

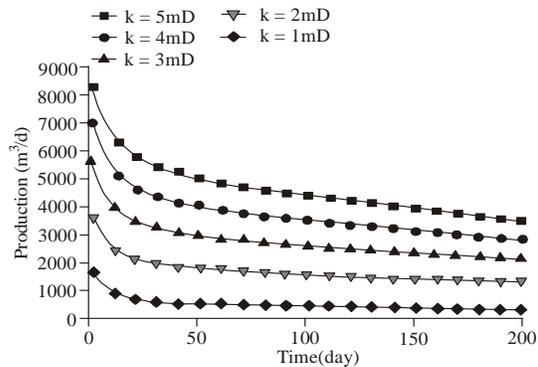


Fig. 3: Relation between daily gas production of CBM well and time under different permeability conditions

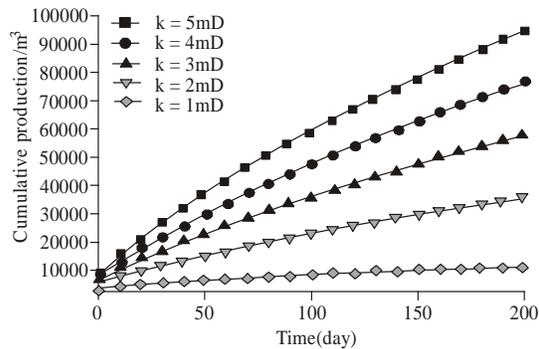


Fig. 4: Relation between cumulative production of CBM well and time under different permeability conditions

daily gas production reaches the maximum at the initial stage and decreases rapidly after 20 days. Ultimately, it tends to a stable value 150 days later. At the same time, we can see the time of daily gas production trending a stable value increases with the permeability of coalbed. For example, the daily gas productions of CBM wells in coalbed with the permeability of 1 and 5 mD take 25 and 150 days to reach the stable values, respectively. The cumulative production of CBM well increases largely

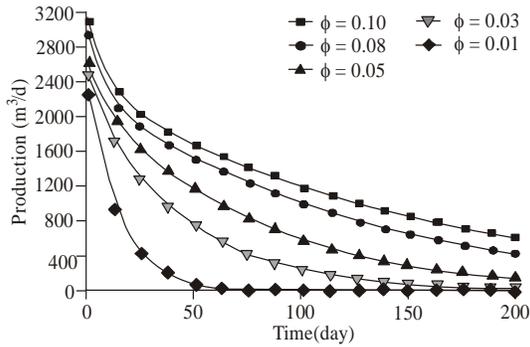


Fig. 5: Relation between daily gas production of CBM well and time under different porosity conditions

with the increase of coalbed permeability (Fig. 4). As shown in Fig. 4, the cumulative production of 200 days increases from 9853 to 95133 m³ when the coalbed permeability changes from 1 to 5 mD, respectively. The comprehensive results address that the increase of coalbed permeability can greatly improve the daily and cumulative productions of CBM well. Therefore, hydraulic fracturing and multiple fracturing technologies are recommended in the CBM exploitation, especially in the coalbed with low permeability.

Porosity: Figure 5 shows the effects of coalbed porosity on the daily gas production of CBM well. As the increase of coalbed porosity, the initial daily gas production increases greatly. Moreover, larger coalbed porosity means higher stable production. In the meantime, we can see the daily gas production of CBM well in coalbed with low porosity decreases speedier than that of CBM well in coalbed with high porosity. For example, the daily gas production of CBM well in coalbed with porosity of 0.01 basically tends to zero after exploitation for 60 days, while that of CBM well in coalbed with porosity of 0.1 reaches the stable production with a value of about 1000 m³/d. It is concluded that the increase of coalbed porosity can significantly improve daily gas production and cumulative production of CBM well.

Well control radius: In the numerical simulations, well control radiuses are valued as 5, 10, 20, 30, 50 and 100 m respectively to get the influences of well control radius on the daily gas production of CBM well (Fig. 6). As shown in Fig. 6, the well control radius has little effect on the initial daily gas production, while its influence gradually becomes significant with the increase of exploitation time. Meanwhile, the production of CBM well with small well control radius reduces quickly with time. Because when the well control radius is small, the area controlled by the CBM well is small and CBM desorption from coalbed is also small. Therefore, CBM extraction will be finished in

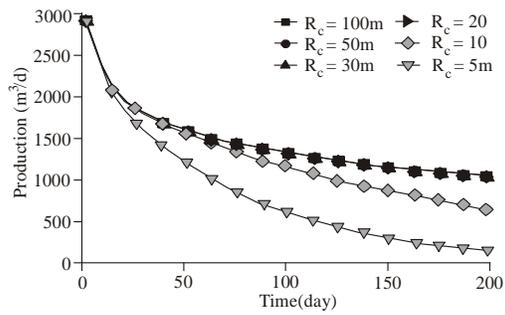


Fig. 6: Relation between daily gas production of CBM well and time under different well control radius conditions

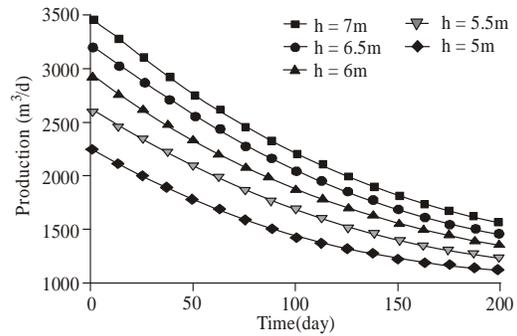


Fig. 7: Relation between daily gas production of CBM well and time under different coalbed thickness conditions

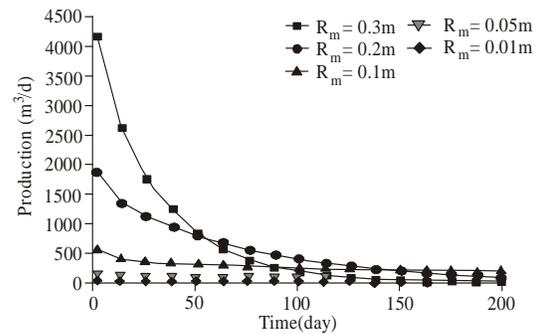


Fig. 8: Relation between daily gas production of CBM well and time under different coal-rock matrix radius conditions

a short time. From Fig. 6, we can also see the production of CBM well increases with the well control radius until it exceeds a critical value. Ultimately, the production no longer changes with the increase of well control radius, indicating the well control radiuses could be optimized to improve the use efficiencies of CBM wells in the actual design. By comparing the results in Fig. 6, the critical value of well control radius is about 20 m. Therefore, the distance between two adjacent CBM wells should not be less than 40 m by the consideration of well use efficiencies.

Coalbed thickness: Figure 7 presents the relation between the daily gas production of CBM well and time under different coalbed thickness conditions. As shown in Fig. 7, the daily gas production increases with coalbed thickness. The initial daily gas production is affected by coalbed thickness seriously, but its influence gradually reduces with the increasing exploitation time. For example, the initial daily gas productions of CBM well in coalbed with thicknesses of 5 and 7 m are 2233 and 3445 m³/d, respectively, increasing about 53.3%. Under the same condition, the productions of two wells are 1115 and 1565 m³/d, respectively after exploitation for 200 days with an increase of 40%.

Radius of coal-rock matrix: CBM is mainly stockpiled in the coal-rock matrix which significantly affects the daily gas production of CBM well. Figure 8 gives the relation between the daily gas production of CBM well and time under different matrix radius conditions. The initial daily gas production of CBM well increases with increasing coal-rock matrix radius. Nevertheless, the daily gas production of CBM well in the coal-rock matrix with large radius reduces more rapidly with the increase of the exploitation time than that in the coal-rock matrix with small radius. When the exploitation time surpasses 150 days, the matrix radius basically has no effect on the daily gas production of CBM well.

CONCLUSION

- Based on Buckley-Leverett equation, the two-phase flow model in unsaturated coalbed is proposed. The calculation equations of daily gas and water production of CBM well are derived from the proposed model. A program is achieved based on the equations. The simulated results are verified by the actual site monitoring values. Moreover, the influence laws of permeability, porosity, well control radius, coalbed thickness and matrix radius on the daily gas production of CBM well are studied.
- Daily gas production of CBM well is well predicted by the model proposed in the study. The calculation results are agreement with the monitoring values with an error of about 7%, which can satisfy the engineering requirement.
- The comprehensive results address that the permeability of coalbed is one of the main influencing factors on the daily gas production of CBM well. Larger porosity means higher initial and stable daily gas production. Appropriate increase of the well control radius can improve the gas production. However, when the well control radius reaches a critical value, it has no effect on the daily gas production. Matrix radius has a great influence

on the initial production, whereas it has small effect on daily gas production at the late exploitation stage. The daily gas production increases with increasing coalbed thickness.

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REFERENCES

- Allaneau, Y. and A. Jameson, 2011. Connections between the filtered discontinuous Galerkin method and the flux reconstruction approach to high order discretizations. *Comput. Methods Appl. Mech. Eng.*, 200(49-52): 3628-3636.
- Arri, L.E., D. Yee and W.D. Morgan, 1992. Modeling coalbed methane production with binary gas sorption. SPE Rocky Mountain Regional Meeting, 18-21 May, Casper, Wyoming, SPE: 24363-MS.
- Jiang, Y.D., X.Y. Yang and L. Xiong, 2011. Multi-field coupling effect on coalbed methane seepage characteristics and numerical simulation. *J. Chong Qing U.*, 34(4): 30-36.
- Lahivaara, T. and T. Huttunen, 2011. A non-uniform basis order for the discontinuous Galerkin method of the acoustic and elastic wave equations. *Appl. Num. Math.*, 61(4): 473-486.
- Liu, X.F., Y.G. Qi and M. Hua, 2011. Inflow performance analysis of single-phase water flow in coalbed methane wells. *Chin. J. Rock Mech. Eng.*, 30(5): 960-967.
- McKee, C.R. and A.C. Bumb, 1987. Flow-testing coalbed methane production wells in the presence of water and gas. *SPE Form. Eval.*, 2(4): 599-608.
- McKee, C.R., A.C. Bumb and R.A. Koenig, 1988. Stress-dependent permeability and porosity of coal and other geologic formations. *SPE Form. Eval.*, 3(1): 81-91.
- Paul, G.W. and W.K. Sawyer, 1990. Validation of 3D coalbed simulators. SPE Annual Technical Conference and Exhibition, 23-26 September, New Orleans, Louisiana, SPE: 20733-MS.
- Ren, S.N., F.M. Ying and C.G. Jian, 2012. Modeling transient flow behavior of a horizontal well in a coal cleat. *Int. J. Coal Geol.*, 92(1): 54-68.
- Sawyer, W.K., G.W. Paul and R.A. Schraufnagel, 1990. Development and application of a 3-d coalbed simulator. Annual Technical Meeting, Jun 10-13, Calgary, Alberta, SPE: 90-119.
- Seidle, J.P. and L.E. Arri, 1990. Use of conventional reservoir models for coalbed methane simulation. CIM/SPE International Technical Meeting, 10-13 June, Calgary, Alberta, Canada, SPE: 21599-MS.

- Siddiqui, S., P.J. Hicks and A.S. Grader, 1996. Verification of Buckley-Leverett three-phase theory using computerized tomography. *J. Petrol. Sci. Eng.*, 15(1): 1-21.
- Wang, T.T., X.Z. Yan, X.J. Yang and H.L. Yang, 2010a. Surface dynamic subsidence prediction above salt cavern gas storage considering the creep of rock salt. *Sci. China Techn. Sci.*, 53: 3197-3202.
- Wang, T.T., X.Z. Yan, X.J. Yang and H.L. Yang, 2010b. Improved Mohr-Coulomb criterion applicable to gas storage caverns in multilaminated salt stratum. *Acta Petrol. Sinica*, 31(6): 1040-1044.
- Wang, T.T., X.Z. Yan and X.J. Yang, 2010c. Collapse pressure of perforated liner casing in CBM exploration basing on plastic hinge model. *J. China Coal Soc.*, 35(2): 273-277.
- Wang, T.T., X.Z. Yan, H.L. Yang and X.J. Yang, 2011a. Stability analysis of the pillars between bedded salt cavern groups by cusp catastrophe model. *Sci. China Techn. Sci.*, 54(6): 1615-1623.
- Wang, T.T., X.Z. Yan, H.L. Yang and X.J. Yang, 2011b. Stability analysis of pillars between bedded salt cavern gas storages. *J. China Coal Soc.*, 36(5): 790-795.
- Xiong, J., J. Liu and J.J. Liu, 2007. Two-phase seepage theory in unsaturated rock and soil based on Buckley-leverett equation. *J. Liaon. Techn. U.*, 26(2): 213-215.
- Yan, X.Z., B.H. Wang and X.J. Yang, 2010a. Finite element optimization method of boundary load of in-situ stress field. *Chin. J. Geotechn. Eng.*, 32(10): 1485-1490.
- Yan, X.Z., Y.T. Zhang, T.T. Wang and X.J. Yang, 2010b. Permitted build-up rate of completion strings in multi-branch CBM well. *J. China Coal Soc.*, 35(5): 787-793.