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Dynamic behavior of coalbed methane flow along the annulus of single-phase production

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Abstract Dynamic behavior of coalbed methane (CBM) flow will provide the theoretical basis to optimize production performance for a given well. A mathematical model is developed to simulate flowing pressures and pressure drops of CBM column from well head to bottom hole. The measured parameters and independent variables of flow rates, flowing pressures and temperatures are involved in CBM producing process along the annulus. The developed relationships are validated against full-scale measured data in single-phase CBM wellbores. The proposed methodology can analyze the dynamic behavior in CBM reservoir and process of CBM flow with an overall accuracy of 2%. The calculating process of flowing pressures involves friction factor with variable Reynolds number and CBM temperature and compressibility factor with gravitational gradients. The results showed that the effect of flowing pressure on CBM column was more obvious than that on CBM and water column accompanied by an increase of dynamic water level. The ratios of flowing pressure on increment of CBM column to the whole column increased with the declined flow rates of water column. Bottom-hole pressure declined with the decreased flowing pressure of CBM column along the annulus. It will lead to the results of the increased pressure drop of CBM column and CBM flow rate in single-phase CBM wellbores.

Keywords Dynamic characteristic · Single-phase CBM wellbore · Flowing pressure of CBM column · Flow rate of CBM column

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1 Introduction

Periodic analysis of flowing pressures can forecast the dynamic behavior in coal reservoirs and solve the common problems of matching the CBM reservoir behavior with wellbore conditions in single-phase CBM wellbores (Mitchell 2011; Mohammed and Enty 2013; Towler et al. 2016). A reliable and accurate approach to predict flowing pressures is essential to design artificial lifting systems and to optimize production performance for the given CBM well. An alternative is to propose a reliable and accurate approach and estimate the flowing pressures and pressure drops in single-phase CBM wellbores with respect to the well liquids and well datum (Osman et al. 2005; Bello and Asafa 2014). In order to calculate the flowing pressures, Rendeiro and Obeida (Rendeiro and Kelso 1988; Obeida and Mosallam 2007) developed the Average Temperature and Pressure method. And Z-factor could be computed by assuming the whole wellbore to be at an average temperature and pressure along the annulus. This methodology does not perform well for most deep CBM wells and is even less reliable for such CBM wells at low gas/liquid ratios. Cullender et al. (Cullender and Smith 1956; Peffer et al. 1988; Guzman et al. 2014) proposed Cullender and Smith methodology for the single-phase well with gas occupying the wellbore. This methodology took the variations in temperature and gas compressibility with depth into account. And the absolute roughness of rough-turbulent flow was 6.0×10^{-4} inches in dry-gas wells. Wang et al. (2014) calculated the flowing pressures and pressure distributions using experimental and numerical simulations. The distributions of temperature and pressure on the bottom of the hole during the SC-CO_2 jet drilling were simulated experimentally and numerically, and the impacts of the nozzle diameter, the jet length, and the inlet pressure of the SC-CO_2 jet were analyzed. Artificial neural networks (ANN) (Osman and Aggour 2002; Mohammadpoor et al. 2010; Li et al. 2017) create models that can recognize highly complex and non-straight-forward problems. ANN provides an integrated approach for the prediction of bottom-hole pressures in multiphase flow. Ashena and Menad (Ashena and Moghadasi 2011; Menad et al. 2018) estimated the flowing pressures using evolved neural networks and grey wolves optimization. ANN with 7 neurons in its hidden layer was utilized to solve the non-straightforward problem of two-phase flow in annulus. Much more promising results were obtained when the highly efficacious tool of ant colony optimization (ACO) was utilized as the next method to optimize the weights and thresholds of the neural networks. The models were developed and tested using 100 field data collected from Algerian fields and covering a wide range of variables. The main problem that ANN models suffer from, is the presence of some inaccuracies caused by the defaulted training algorithms that trap in local minima.

The above relationships generally conducted various theoretical analytic approaches of conventional oil fields and dry-gas wells to calculate the flowing pressures and pressure drops. Therefore, these modeling procedures do not give the desired results to predict the flowing performance along the annulus. The main reason is that there exists the differences between coal geology and gas formations (Yao and Ge 2011; Liu 2013; Liu et al. 2018; Underschultz et al. 2018), including low water production, high dynamic water level, short stroke and rapid dropping down of pumping speed. Another aspect to consider is that the flowing pressures in CBM wellbores have not been further developed and the available models cannot satisfy the accuracy requirements in engineering design.

A mathematical model is developed to simulate flowing pressures and pressure drops of CBM column from well head to bottom hole. The measured parameters and independent variables of flow rates, flowing pressures and temperatures were involved in CBM producing process along the annulus. The flowing pressures were predicted on the basis of single-phase CBM wellbore conditions along the annulus stretching over a wider range in order to predict the dynamic characteristics of CBM flow in single-phase CBM wells and provide the theoretical basis to design artificial lifting systems.

2 Model development of CBM flow

This work presents a methodology that involves a numerical integration technique to calculate flowing pressures of CBM column based on the gas flow equation and well flowing model. And the methodology would provide accurate results while it involves friction factor with variable Reynolds number and CBM temperature and compressibility factor with gravitational gradients. The relationship about energy among the tubing, casing and their annulus in single-phase CBM wellbore stems from the mechanical energy equation. This energy balance (Mattar and McNeil 1998; Mohammed et al. 2011) can be expressed for steady-state flow, as follows:

$$\frac{\mathrm{d}p}{\mathrm{d}L} = g\rho \sin\theta + 0.5\frac{f\rho}{d}v^2 + \rho v\frac{\mathrm{d}v}{\mathrm{d}L} + \rho\frac{\mathrm{d}w}{\mathrm{d}L} \quad (1)$$

where d is the diameter of CBM column in m, f is the friction factor along the annulus, L is the length of whole wellbore in m, p is the pressure of CBM column in Pa, v is the flowing velocity of CBM column in m/s, θ is the angle of CBM column in rad, and ρ is the density of CBM column in kg/m^3.

Two parameters are introduced to calculate pressures of CBM column. They are the flowing velocity and density of CBM column in single-phase CBM wells.

$$v = 5.094 \times 10^{-6}\frac{Zq_{sc}T}{d^2p} \quad (2)$$

$$\rho = 3.485 \times 10^{3}\frac{\gamma_c p}{ZT} \quad (3)$$

Considering CBM column flow from the bottom hole to well head along the annulus between tubing and casing, the kinetic energy loss is ignored in the energy balance. The energy balance for calculating pressure of CBM column can be expressed as follows:

$$\frac{\mathrm{d}p}{\mathrm{d}h} + 3.419 \times 10^{4}\gamma_c\frac{p}{ZT} + 4.520 \times 10^{-8}\frac{\gamma_c f}{d^5}\frac{ZT}{p}q_{sc}^2 = 0 \quad (4)$$

where h is the coordinate of well depth in m, q_{sc} is flow rate of CBM column in m^3/d, T is the temperature along CBM column in K, Z is compressibility factor of CBM column, and γ_c is specific gravity of CBM column.

The estimation of pressures of CBM column involves the energy losses of friction resistance and the hydrostatic head in CBM wellbore. Upon transformation of variable and integration, the energy equation can be simplified to the following pressure formula.

$$3.418 \times 10^{-2}\gamma_c h_c = \int_{p_{hf}}^{p_{tcf}} \frac{ZpT}{p^2 + 1.322 \times 10^{-18} Z^2 f d^{-5} q_{sc}^2 T^2} \mathrm{d}p \tag{5}$$

The CBM column flows upward along the annulus between tubing and casing, and hence the flowing velocity of CBM column is given by the formula, as follows:

$$v = \frac{4q_{sc}}{\pi\left(d_c^2 - d_t^2\right)} \tag{6}$$

Consequently, the energy equation can be modified to the following equation, which is used in computing of pressure of CBM column in single-phase CBM wellbores.

$$\gamma_c h_c = \int_{p_{hf}}^{p_{tcf}} \frac{29.257ZpT}{p^2 + \frac{1.322\times10^{-18}Z^2 f q_{sc}^2 T^2}{(d_t+d_c)^2(d_c-d_t)^3}} \mathrm{d}p \tag{7}$$

where d_c is the casing diameter in m, d_t is the tubing diameter in m, h_c is the well depth of the whole CBM column in m, p_{hf} is the well-head pressure in MPa, and p_{tcf} is the flowing pressure on dynamic water level in single-phase CBM wellbores in MPa.

compressibility factor of CBM column, Z, illustrates the ratio of true volume to ideal volume under the condition of identical quality. This factor can be obtained from Sanding–Katz curves of compressibility factor. The factor is known as a function of pseudoreduced density, ρ_{pr}, and pseudoreduced temperature, T_{pr}, for the pure CBM column. An explicit factor, which is an accurate mathematical approximation (Sutton 2008; Mora and Wattenbarger 2009), is developed due to experimental results and given by:

$$Z = \frac{0.299 - 2.188 \times 10^{-2}\gamma_c - 4.689 \times 10^{-3}\gamma_c^2}{\rho_{pr} T_{pr}} \exp\left[-1.2\left(\frac{T_{pr} - 1}{T_{pr}}\right)^2\right] \tag{8}$$

$$T_{pr} = 103.89 + 183.33\gamma_c - 39.722\gamma_c^2 \tag{9}$$

The CBM flow through the annulus between tubing and casing in single-phase CBM wells always results in some energy losses. These losses are mainly caused by the friction related to pipe roughness and viscosity effects. Since the friction losses cannot be measured directly, the correlation is proposed to determine the friction factor (Yalniz and Ozkan 2001; Langelandsvik et al. 2005). This factor is a function of both relative roughness in wellbore and Reynolds number (Yalniz and Ozkan 2001; Langelandsvik et al. 2005) of CBM column. Relative roughness in wellbore is usually described in terms of the ratio of absolute roughness, e, to annulus diameter ($d_c - d_t$). This corresponds to the absolute roughness of the annulus in CBM wellbores and has been proved to be experimentally correct for different test CBM columns based on the laboratory investigation. Therefore, an explicit correlation for the friction factor of CBM column in pumping wellbores is developed, and can be given by:

$$f^{-0.5} = 1.14 - 2\lg\left(\frac{e}{d_c - d_t} + \frac{21.25}{Re^{0.88}}\right) \tag{10}$$

Since Newtonian viscous force is related to the lubrication perimeter, Reynolds number (Re) of CBM column in the annulus of single-phase CBM wells can be determined, as follows:

$$Re = 1.78 \times 10^{-5} \frac{q_{sc}\gamma_c}{\mu_c(d_t + d_c)} \tag{11}$$

where μ_c is the viscosity of flowing CBM column in mPa s.

The integrand of pressure drop, I, is introduced and it is defined as follows:

$$I = \frac{\frac{p}{ZT}}{\left(\frac{p}{ZT}\right)^2 + 1.32 \times 10^{-18} \frac{q_{sc}^2 f}{(d_c-d_t)\cdot\left(d_c^2-d_t^2\right)^2}} \tag{12}$$

The mathematical model of flowing pressures for CBM column is solved with numerical integration due to the numeric analysis. And the procedure involves iterative calculations with regard to two parts of CBM column in single-phase CBM wells.

$$6.84 \times 10^{-2}\gamma_c h_c = \left(p_{mf} - p_{hf}\right)\left(I_{mf} + I_{hf}\right) + \left(p_{tcf} - p_{mf}\right)\left(I_{tcf} + I_{mf}\right) \tag{13}$$

For the mathematical model of upper pressure of CBM column, the flowing pressure for middle part of the whole CBM column, p_{mf}, can be determined due to the measurements of well-head pressure in single-phase CBM wells. And then the equation for upper pressure of CBM column can be given by:

$$3.42 \times 10^{-2}\gamma_c h_c = \left(p_{mf} - p_{hf}\right)\left(I_{mf} + I_{hf}\right) \tag{14}$$

The mathematical model can be solved for upper pressure of CBM column, as follows:

(1) Calculate the integrand I_{hf} and the product of γ_c and h_c in single-phase CBM wellbores.

(2) Complete the initial computation with the help of the integrand I_{mf} equal to I_{hf}.

(3) Determine the flowing pressure, p_{mf}, and the integrand, I_{mf}, for the middle part of the whole CBM column in single-phase CBM wells.

(4) Iterate by returning to Step 3 until the accurate result of p_{mf} is obtained.

For the mathematical model of lower pressure of CBM column, the flowing pressure on dynamic water level in single-phase CBM wellbores, p_{tcf}, can be determined due to the results of pressure for middle part of the whole CBM column along the annulus. And then the equation for lower pressure of CBM column can be given by:

$$p_{tcf} = p_{hf} + \Delta p_c = p_{hf} + \frac{0.205\gamma_c h_c}{I_{hf} + 4I_{mf} + I_{tcf}} \quad (15)$$

The mathematical model can be solved for lower pressure of CBM column, as follows:

(1) Complete the initial computation with the help of the integrand I_{bf} equal to I_{mf}.
(2) Determine the flowing pressure, p_{tcf}, and the integrand, I_{tcf}, on dynamic water level in wellbores.
(3) Iterate by returning to Step 2.

The flowing pressure on dynamic water level in single-phase CBM wellbores, p_{tcf}, can be iterated as the sum of pressure of well head and CBM column. Repeat the above procedure until the desired accuracy of p_{tcf} is obtained.

3 Flowing pressures in single-phase CBM wellbores

The complete CBM producing process can be divided into several phases including single-phase water flow, two-phase (CBM and water) flow and single-phase CBM flow (Okuszko et al. 2008; Liu et al. 2011, 2019; Sugiarto et al. 2015). Undersaturated coal reservoirs may produce water mainly for a substantial period of time until desorption pressure is reached (Lyubarskii and Ivanov 1989; Boltenko 2013; Smith et al. 2019). And then the coal reservoirs produce water mostly and little CBM and exhibit single-phase water flowing performances (Vicki and Paul 2002; Clarkson et al. 2007; Liu et al. 2017; Fan et al. 2019). Therefore, the bottom-hole pressures are affected by well-head pressure, pressure drops of CBM column and water column in producing wellbores for single-phase water flow. The CBM column flows upward while the water column flows downward along the annulus between tubing and casing. And hence the flowing pressures can be found by the CBM and water flow formulae.

The flowing pressure for middle part of the whole CBM column, p_{mf}, can be calculated due to the measurements of well-head pressure in single-phase water wellbores, as follows:

$$p_{mf} = p_{hf} + 3.42 \times 10^{-2} \frac{\gamma_c h_c}{I_{mf} + I_{hf}} \quad (16)$$

The flowing pressure on dynamic water level in single-phase water wellbores, p_{scf}, can be determined based on the results of pressure for middle part of the whole CBM column, as follows:

$$p_{scf} = p_{hf} + 0.205 \frac{\gamma_c h_c}{I_{hf} + 4I_{mf} + I_{scf}} \quad (17)$$

As shown in Fig. 1, bottom-hole pressure of single-phase water flow, p_{bf}, can be determined as the sum of well-head pressure, p_{hf}, flowing pressure of CBM column, Δp_c, and flowing pressure of water column, Δp_w, in pumping wellbores.

$$p_{bf} = p_{hf} + \Delta p_c + \Delta p_w = p_{hf} + 0.205 \frac{\gamma_c h_c}{I_{hf} + 4I_{mf} + I_{cf}} + \rho_w g h_w \quad (18)$$

where h_w is the well depth of water column in m, and ρ_w is the density of water column in kg/m^3.

The coal reservoirs may produce CBM mostly during the phase of single-phase CBM flow (Borowsky and Wei 2006; White and Smith 2012; Tang et al. 2016). And hence the CBM wellbores exhibit single-phase flowing performances for at least a portion of their producing process. The bottom-hole pressures are affected by well-head pressure and pressure drop of CBM column in producing wellbores for single-phase CBM flow. The value of well-head pressure can be recorded by the pressure gauges. The CBM column flows upward in the wellbore, and hence the pressure can be found by the CBM flow formulae. Knowing the values of these pressures, bottom-hole pressures of single-phase CBM wellbores, p_{bf}, can be

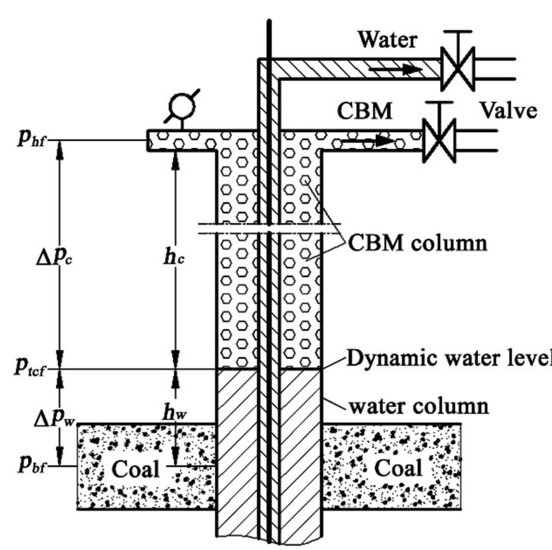


Fig. 1 The components of flowing pressures and pressure drops in single-phase CBM wells

determined as the sum of well-head pressure, p_{hf}, and pressure of CBM column, Δp_c, in single-phase CBM wellbores.

4 Application and interpretation

4.1 Field application

The dynamic characteristics of CBM column flow are clarified by the examples of Hancheng coalfield in Ordos Basin, China. The CBM wells in Hancheng coalfield make continuous production and accumulate a lot of pumping data. The producing characteristics that might influence flowing performances in the wellbores were determined upon the single-phase flow properties.

The operational parameters were selected from the CBM wells in Hancheng coalfield, including: well depth of the whole CBM column, 430 m; CBM langmuir pressure in coal reservoirs, 3.50 MPa; tubing diameter, 2 $^{7}/_{8}$ in.; casing diameter, 7.0 in.; specific gravity of CBM column, 0.58; density of water column, 1015 kg/m^3; and flowing viscosity of CBM column and water column, 1.70×10^{-2} mPa s and 7.85×10^{-4} Pa s, respectively.

The parameters that might influence CBM production are measured by pressure sensors, temperature sensors and flow meters. To clarify CBM producing process along the annulus between tubing and casing, the main measured parameters and independent variables are presented in Table 1. These independent variables are composed of flow rates, flowing pressures and temperatures selected in single-phase CBM wellbores.

4.2 Results and interpretations

To evaluate the accuracy of this proposed methodology, the predicted parameters and variables of flow rates, flowing pressures and temperatures are selected from single-phase CBM wellbores. Predicted variables of flowing pressures and pressure drops using the developed algorithm in single-phase CBM wellbores are shown in Table 2.

Predicted variables of bottom-hole pressure and the percent error between the measured and predicted total pressures in the Average Temperature and Pressure, Cullender and Smith and the proposed methodology are shown in Table 3. As a result, the maximum relative errors are determined to be − 11.2%, − 10.4%, and − 3.7%, respectively. And the average relative errors are predicted to be 3.0%, 2.9%, and 1.1%, respectively. Consequently, the average relative errors can be reduced by 1.9% and 1.8% using the proposed methodology.

Table 3 shows the flowing pressures and errors for single-phase CBM wellbores using Average Temperature and Pressure methodology. And the errors are calculated between − 11.2% and 4.3%. *Z*-factor could be computed by assuming the whole wellbore to be at an average temperature and pressure along the annulus. This methodology does not perform well for most deep and low gas/liquid ratio CBM wells.

Table 3 shows the flowing pressures and errors for single-phase CBM wellbores using Cullender and Smith methodology. And the errors are evaluated between − 10.4% and 4.8%. The calculation of flowing pressures took the variations in gas compressibility and temperature with depth into account. However, this methodology was proposed for the single-phase well with gas occupying the

Table 1 Measured parameters and selected variables in single-phase CBM wellbores

Well point	Dynamic water level h_c (m)	Flow rate of CBM q_{sc} (m^3/d)	Flow rate of water q_w (m^3/d)	Well-head pressre p_{hf} (MPa)	Flowing pressure on dynamic level p_{tch} (MPa)	Measured bottom-hole pressure p_{bf} (MPa)	Well-head temperature T_h (K)
1	160	6721	35.7	0.451	0.455	1.328	285.79
2	338	6063	40.8	1.106	1.137	1.482	286.15
3	389	5796	37.6	1.313	1.372	1.579	286.18
4	396	5415	35.5	1.458	1.516	1.707	286.20
5	402	4162	33.8	1.124	1.155	1.363	286.21
6	418	4058	28.3	1.742	1.801	1.908	287.29
7	426	3925	32.7	1.785	1.844	1.919	288.05
8	431	3611	23.5	2.002	2.073	2.141	288.67
9	436	3694	22.4	1.909	1.968	2.016	289.77
10	439	3327	18.2	2.157	2.216	2.252	289.83

Note The selected CBM wells have been investigated for many years in Hancheng coalfield

Table 2 Predicted variables of flowing pressures and pressure drops using the developed algorithm

Well point	Upper pressure of CBM column Δp_{uf} (MPa)	Pressure of CBM column at midpoint Δp_{mf} (MPa)	Lower pressure of CBM column Δp_{lf} (MPa)	Pressure of CBM column Δp_c (MPa)	Flowing pressure on dynamic level p_{tch} (MPa)	Column pressure of CBM and water Δp_t (MPa)
1	0.0023	0.453	0.00291	0.0052	0.456	0.922
2	0.0142	1.120	0.0143	0.0284	1.134	0.393
3	0.0322	1.345	0.0322	0.0643	1.377	0.222
4	0.0318	1.490	0.0321	0.0639	1.5220	0.203
5	0.0163	1.140	0.0159	0.0321	1.156	0.193
6	0.0276	1.770	0.0272	0.0547	1.797	0.106
7	0.0286	1.814	0.0290	0.0575	1.843	0.0777
8	0.0323	2.034	0.0318	0.0641	2.066	0.0666
9	0.0271	1.936	0.0345	0.0616	1.971	0.0469
10	0.0349	2.192	0.0349	0.0697	2.227	0.0346

Table 3 Predicted variables of bottom-hole pressure and relative error for single-phase CBM wellbores

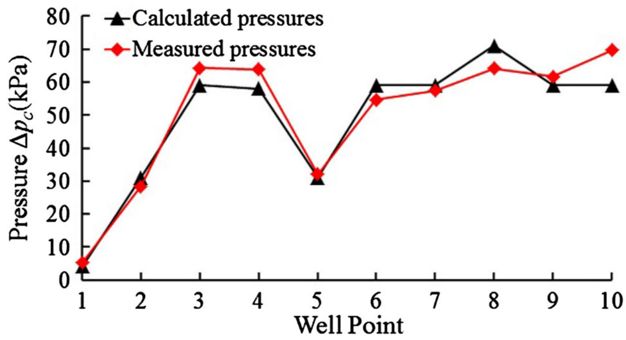
Well point	Average temperature and pressure method		Cullender and Smith methodology		The proposed methodology	
	Predicted bottom-hole pressure p_{bf} (MPa)	Error E (%)	Predicted bottom-hole pressure p_{bf} (MPa)	Error E (%)	Predicted bottom-hole pressure p_{bf} (MPa)	Error E (%)
1	1.476	− 11.2	1.466	− 10.4	1.378	− 3.7
2	1.540	− 3.9	1.547	− 4.4	1.527	− 3.1
3	1.612	− 2.1	1.602	− 1.5	1.599	− 1.3
4	1.743	− 2.1	1.737	− 1.8	1.725	− 1.0
5	1.305	4.3	1.297	4.8	1.349	1.1
6	1.887	1.1	1.873	1.9	1.903	0.3
7	1.932	− 0.7	1.911	0.4	1.920	− 0.07
8	2.114	1.3	2.118	1.1	2.133	0.4
9	2.046	− 1.5	2.038	− 1.1	2.018	− 0.06
10	2.279	− 1.2	2.284	− 1.4	2.261	− 0.4

wellbore. And the absolute roughness of rough-turbulent flow is 6.0×10^{-4} inches in dry-gas wells.

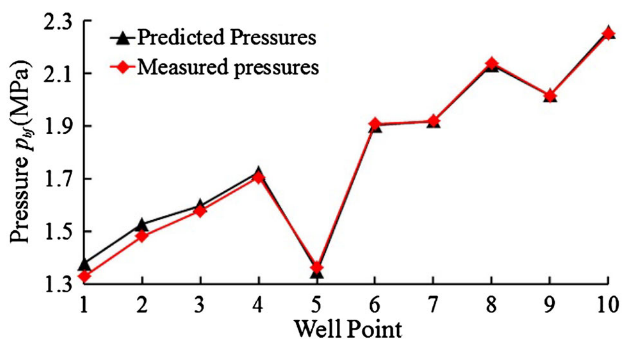
Comparison of flowing pressures of CBM column and bottom hole between the predicted and measured results using the proposed methodology along the annulus in single-phase CBM wellbores is shown in Fig. 2. The proposed methodology is validated against full-scale experimental data measured. The numerical results of flowing pressures of CBM column and bottom hole accord well with the experimental results in single-phase CBM wells. It can be seen from Fig. 2a, b that the maximum relative error of predicting flowing pressure of CBM column can be less than 4.7%. The calculating process of flowing pressures involves friction factor with variable Reynolds number and CBM temperature and compressibility factor with gravitational gradients in single-phase CBM wells. As a result, the developed relationships can analyze the dynamic behavior in CBM reservoir and process of CBM flow with an overall accuracy of 2%.

Figure 3 shows the variation of flowing pressures of well head, CBM column and CBM and water column with time in single-phase CBM wellbores. The flowing pressures along the annulus can be divided into four pressures of well-head pressure, p_{hf}, pressure drop of CBM column, Δp_c, pressure drop of CBM and water column, Δp_t, and bottom-hole pressure, p_{bf}. The flowing pressures along the annulus can fully reflect dynamic characteristics of CBM producing process because of the combination of dynamic water level and flow rates of CBM column and water column.

Figure 4 shows the variation of pressure ratios on increment of CBM column to the whole column with well depth during CBM producing process in pumping wellbores. The ratio of flowing pressure is a function of



(a) Flowing pressures of CBM column



(b) Bottom-hole pressures

Fig. 2 Comparison of flowing pressures between predicted and measured results in single-phase CBM wellbores

dynamic water level along the annulus. The ratios of flowing pressure on increment of CBM column to the whole column are relatively high during the phase of single-phase CBM flow. And the average ratio of flowing pressure is calculated to be 32%. Consequently, the effect of CBM column pressure should not be neglected during the process of predicting flowing pressures along the annulus. At the same time, the effect of flowing pressure on CBM column is more obvious than that on CBM and water

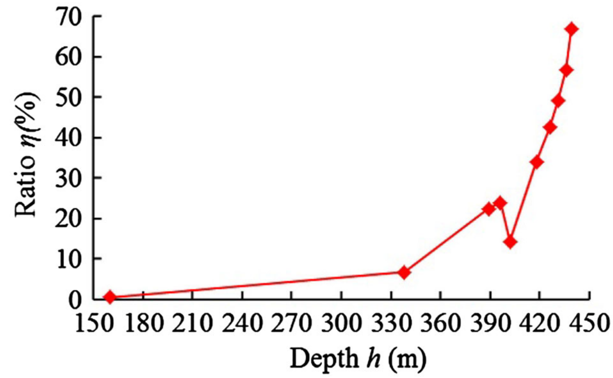


Fig. 4 The ratios of flowing pressure on increment of CBM column to the whole column along the annulus

column accompanied by an increase of dynamic water level. The ratios of flowing pressure on increment of CBM column to the whole column increase with the declined flow rates of water column. The ratios of flowing pressure enhance from 0.6% to 24% and then up to 67% while dynamic water levels along the annulus increase from 160 m to 439 m.

Figure 5 depicts the relationships between flowing pressure of CBM column and CBM production in single-phase CBM wellbores. The bottom-hole pressure enhances accompanied by an increase of flowing pressure of CBM column along the annulus. And this will lead to the results of the declined CBM production in single-phase CBM wellbores. It can be seen from the figure that flow rates of CBM column enhance from 3327 to 6721 m^3/d with the declined pressures of CBM column from 69.7 to 5.2 kPa along the annulus.

Figure 6 shows the effect of pressure drops on flow rate of CBM column along the annulus in single-phase CBM wellbores. The flow rate of CBM column is a function of pressure drop between bottom-hole pressure and Langmuir pressure along the annulus. There is a positive proportion between pressure drop and flow rate of CBM column. The

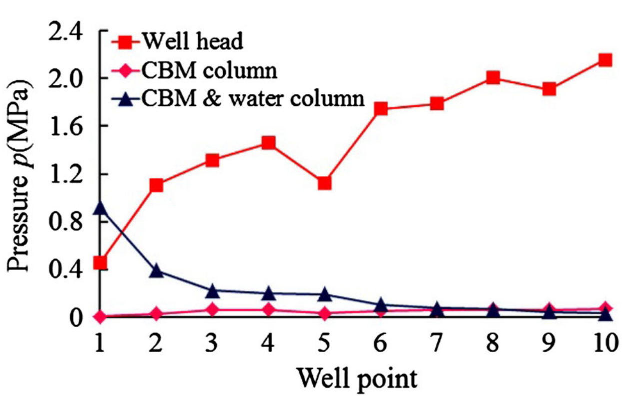


Fig. 3 The variation of flowing pressures with pumping time along the annulus in wellbores

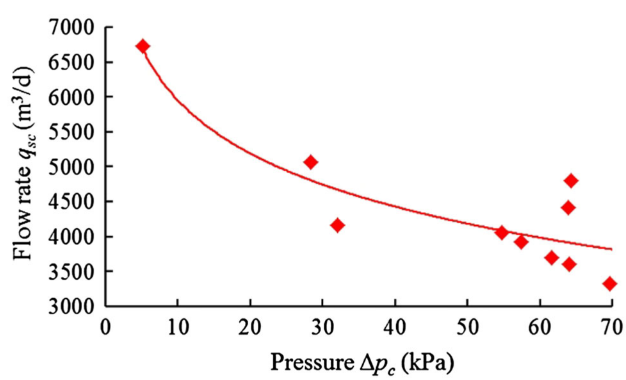


Fig. 5 The effect of flowing pressure on flow rate of CBM column along the annulus in wellbores

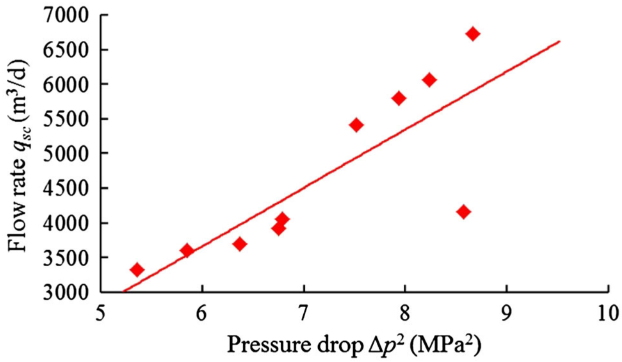


Fig. 6 The effect of pressure drop on flow rate of CBM column along the annulus in wellbores

increased pressure drop of CBM column is beneficial to CBM desorption in coal reservoirs, leading to the results of the improved CBM flow rate in single-phase CBM wellbores. The flowing pressures of CBM column and CBM and water column enhance the imbalance of pressure between well head and bottom hole in single-phase CBM wells. Flow rates of CBM column vary in a large scale with pressure drops of CBM column during CBM producing process. It can be seen from Fig. 6 that there is a point (8.58 MPa^2, 4162 m^3/d) that clearly deviates from the straight line. The main reason is that the decreased flowing pressures of well head and CBM column and the increase of the falling speed of dynamic water level will reduce bottom-hole pressure and enhance the imbalance of pressure drop.

5 Conclusions

This work presents a methodology that involves a numerical integration technique to predict and analyze the dynamic characteristics of CBM column in wellbores. This provides the theoretical basis to analyze the dynamic behavior in CBM reservoir and process of CBM flow and solve the forthcoming problems in single-phase CBM wellbores. It comes out that:

(1) The calculating process of flowing pressures involves friction factor with variable Reynolds number and CBM temperature and compressibility factor with gravitational gradients. The developed relationships are validated against full-scale measured data in single-phase CBM wellbores.
(2) Well-head pressure, pressure drop of CBM column and CBM and water column, and bottom-hole pressure along the annulus can fully reflect dynamic characteristics of CBM producing process because of the combination of dynamic water level and flow rates of CBM column and water column.
(3) The effect of flowing pressure on CBM column is more obvious than that on CBM and water column accompanied by an increase of dynamic water level. The ratios of flowing pressure on increment of CBM column to the whole column increase from 0.6% to 24% and then up to 67% while dynamic water levels along the annulus increase from 160 to 439 m.
(4) The decreased pressures of CBM column from 69.7 to 5.2 kPa will lead to the results of the decreased bottom-hole pressures from 2.3 to 1.3 MPa and the increased flow rates of CBM column from 3327 up to 6721 m^3/d.

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