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Production decline type curves analysis of a finite conductivity fractured well in coalbed methane reservoirs

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Abstract: Production decline type curves analysis is one of the robust methods used to analyze transport flow behaviors and to evaluate reservoir properties, original gas in place, etc. Although advanced production decline analysis methods for several well types in conventional reservoirs are widely used, there are few models of production decline type curves for a fractured well in coalbed methane (CBM) reservoirs. In this work, a novel pseudo state diffusion and convection model is firstly developed to describe CBM transport in matrix systems. Subsequently, based on the Langmuir adsorption isotherm, pseudo state diffusion and convection in matrix systems and Darcy flow in cleat systems, the production model of a CBM well with a finite conductivity fracture is derived and solved by Laplace transform. Advanced production decline type curves of a fractured well in CBM reservoirs are plotted through the Stehfest numerical inversion algorithm and computer programming. Six flow regimes, including linear flow regime, early radial flow in cleat systems, interporosity flow regime, late pseudo radial flow regime, transient regime and boundary dominated flow regime, are recognized. Finally, the effect of relevant parameters, including the storage coefficient of gas in cleat systems, the transfer coefficient from a matrix system to the cleat system, the modified coefficient of permeability, dimensionless fracture conductivity and dimensionless reservoir drainage radius, are analyzed on type curves. This paper does not only enrich the production decline type curves model of CBM reservoirs, but also expands our understanding of fractured well transport behaviors in CBM reservoirs and guides to analyze the well’s production performance.

Keywords: Coal bed methane; Langmuir adsorption isotherm; production; type curves; fractured well

PACS: 47.56.+r

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>β_m</td>
<td>modify coefficient of permeability</td>
</tr>
<tr>
<td>γ</td>
<td>free gas storage coefficient</td>
</tr>
<tr>
<td>Λ</td>
<td>transfer coefficient from matrix systems to cleat systems</td>
</tr>
<tr>
<td>μ</td>
<td>gas viscosity (mPa·s)</td>
</tr>
<tr>
<td>ω</td>
<td>storage coefficient of gas in cleat systems</td>
</tr>
<tr>
<td>ψ_fD</td>
<td>dimensionless pressure in cleat systems in Laplace space</td>
</tr>
<tr>
<td>ψ_mD</td>
<td>dimensionless pressure in matrix systems in Laplace space</td>
</tr>
<tr>
<td>η_D</td>
<td>dimensionless rate in Laplace space</td>
</tr>
<tr>
<td>ψ_fD</td>
<td>dimensionless pressure in cleat systems</td>
</tr>
<tr>
<td>ψ_mD</td>
<td>dimensionless pressure in matrix systems</td>
</tr>
<tr>
<td>ρ_f</td>
<td>gas density in cleat systems under the reservoir condition (kg/m^3)</td>
</tr>
<tr>
<td>ρ_m</td>
<td>gas density under the reservoir condition (kg/m^3)</td>
</tr>
<tr>
<td>φ_f</td>
<td>porosity in cleat systems (decimal)</td>
</tr>
<tr>
<td>b_m</td>
<td>slippage factor</td>
</tr>
<tr>
<td>c_{gm}</td>
<td>gas compressibility in matrix systems (MPa⁻¹)</td>
</tr>
<tr>
<td>C_m</td>
<td>gas molar concentration (mol/m³)</td>
</tr>
<tr>
<td>c_{im}</td>
<td>total compressibility in matrix systems (MPa⁻¹)</td>
</tr>
<tr>
<td>D</td>
<td>gas diffusion coefficient (m²/s)</td>
</tr>
<tr>
<td>F_{cD}</td>
<td>dimensionless fracture conductivity</td>
</tr>
<tr>
<td>h</td>
<td>reservoir thickness (m)</td>
</tr>
<tr>
<td>k_{fh}</td>
<td>permeability in cleat systems (m²)</td>
</tr>
<tr>
<td>k_f</td>
<td>fracture permeability (μm²)</td>
</tr>
<tr>
<td>L</td>
<td>reference length (m)</td>
</tr>
<tr>
<td>M</td>
<td>gas relative molecular mass (kg/mol)</td>
</tr>
</tbody>
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1 Introduction

Coal bed methane (CBM) reservoirs are considered as an important unconventional gas reservoirs since these ones have made a significant contribution to the world gas production [1–3]. Coal beds are naturally fractured reservoirs with cleat network and matrix blocks. Compared with conventional gas reservoirs, CBM reservoirs have complex reservoir characteristics, such as adsorption/desorption in matrix systems [4–6]. Meanwhile, different coal seams have different compositions (e.g. thermal maturity, pressure and adsorption/desorption capacity, etc.). Therefore, each CBM reservoir has different transport behaviors. As it’s known, transient pressure analysis (well testing analysis) and production decline analysis are practical and powerful tools to characterize the unsteady flow behaviors of reservoirs [7–9] and to recognize formation parameters. In recent years, production analysis for reservoirs characterization is approaching the popularity of transient pressure analysis, but there are limited production decline type curves models and methods for CBM reservoirs [10].

In the past decades, much progresses have been made. Considering the adsorption/desorption, Anbarci and Ertekin [11] investigated the transient flow behaviors of vertical well for single phase gas flow in CBM reservoirs. Pinzon and Patterson [12], and Clarkson et al. [13] analyzed production data for a dry gas CBM well and taken radial flow type curves of CBM data to account for gas desorption, respectively. Assuming a constant pressure inner boundary condition, Mohaghegh and Ertekin [14] obtained radial flow type curves using a numerical simulator. Later, Guo et al. [15] investigated numerical model of a CBM reservoirs. Aminian et al. [16] also applied a numerical simulator to generate production type curves by defining a new set of dimensionless variables. Aminian and Ameri [17] developed a numerical reservoir model of CBM to analyze the well’s performance. Later, Clarkson et al. [13] studied the production decline of a fractured and horizontal CBM well by using Fetkovich type curves method to evaluate reservoir information quantitatively. Nie et al. [18] and Guo et al. [15] investigated the transient transport behavior and production decline type curves of a horizontal well in CBM reservoirs by using the semi-analytical method.

But the aforementioned transient transport models of CBM reservoirs only considered diffusion mechanism in matrix [19–25]. However, King and Ertekin [26] and Li et al. [27] stated that the more rigorous model of CBM should also take pressure transient (convection) in matrix systems into consideration. In addition, although most aforementioned studies have utilized radical flow type curves of CBM vertical wells and horizontal wells to match the production data, there are few attempts to study the production decline type curves for CBM fractured well.

Thus, this paper focuses on generating production decline type curves for a CBM well with a finite conductivity vertical fracture by considering diffusion and convection (Darcy flow) in matrix systems at same time. Firstly, the CBM transport model coupled with pseudo state diffusion and convection in matrix system is developed. Secondly, a production decline model for a single phase CBM fractured well is derived and solved by using the semi-analytical method. Thirdly, the model solution is verified by a simplified model, then production decline type curves are plotted, their characteristics and the effects of related parameters are analyzed. The proposed model of a finite conductive fracture well in a CBM reservoirs does not only expand our understanding of fractured well behaviors in...
CBM reservoirs, but also enriches the production decline type curves model in CBM reservoirs.

2 Model construction

CBM reservoirs are known as a typical dual porosity media, which is consisted of cleat networks and matrix systems (Figure 1a). The physical properties of the matrix and cleat of the CBM formulation are independent. Each matrix element is assumed as spherical in shape. The absorbed gas will be desorbed from matrix blocks. Darcy flow in cleats, pseudo-steady state flow, including diffusion driven by concentration gradient, and Darcy flow driven by the pressure gradient in the matrix elements’ micropores are considered (Figure 1b).

Based on flow mechanisms in coal matrixs, the flow velocity is dominated by both the pressure gradient and the concentration gradient. Referencing the research result of Ertekin et al. [28], the velocity in the matrix can be added by the velocity of the pressure gradient and the concentration gradient linearly, which can be expressed as:

\[ v_m = v_m^p + v_m^c = \frac{k_m}{\mu} \frac{\partial p_m}{\partial r_m} + \frac{MD}{\rho_m} \frac{\partial C_m}{\partial r_m} \]  

where \( v_m \) is the flow velocity in the matrix, \( m^2/s; v_m^p \) is the velocity caused by the pressure gradient, \( m^2/s; v_m^c \) is the velocity caused by the concentration gradient, \( m^2/s; r_m \) is the spherical radius for a matrix element, \( m; \mu \) is the gas viscosity, mPa.s; \( \rho_m \) is the gas density under the reservoir condition, kg/m\(^3\); \( p_m \) is the pressure in the matrix system, MPa; \( C_m \) is the gas molar concentration, mol/m\(^3\); \( M \) is the gas relative molecular mass, kg/mol; \( D \) is the gas diffusion coefficient, m\(^2\)/s.

Further, inserting the gas state equation into Eq. (1), Eq. (1) can be rewritten as:

\[ v_m = \frac{k_m}{\mu} \left(1 + \frac{\mu c_{gm} D}{k_m} \right) \frac{\partial p_m}{\partial r_m} = \frac{k_m}{\mu} \left(1 + \frac{b_m p_m}{\rho_m} \right) \frac{\partial p_m}{\partial r_m} \]  

(2)

where \( c_{gm} \) is the gas compressibility in matrix systems, MPa\(^{-1}\); \( b_m \) is the slippage factor, and \( \beta_m \) is the modified coefficient of permeability, defined as:

\[ \beta_m = 1 + \frac{b_m p_m}{\rho_m} \]  

(3)

2.1 Physical conceptual model and its assumptions

Due to the features of low permeability and porosity in CBM reservoirs, a fractured well is one of the common well types to develop CBM reservoirs. Thereby, a fractured well in a CBM reservoir with a radial coordinate system is considered in this paper (Figure 2), and assumptions of the physical model are as follows:

1. The CBM reservoir is assumed as a spherical dual porosity model (Swaan [29]) with uniform thickness, initial pressure, permeability, Langmuir volume, Langmuir pressure and porosity;
2. A fractured well is located in the center of the reservoir, and produces gas at a constant rate or at a constant wellbore flowing pressure, whose external boundaries are closed;
3. The hydraulic fracture penetrates the formation vertically, and has a half fracture length \( x_f \) a permeability \( k_f \), a finite conductivity \( F_{CD} \) and a width \( W_f \);
4. The desorption occurring at the matrix surface can be described by the Langmuir adsorption isotherm equation, and both pseudo steady diffusion and convection are considered in matrix systems; while the flow in cleat systems obeys Darcy’s law [18, 24];
5. The influence of gas gravity is neglected, and the reservoir is isothermal.

2.2 Mathematical modeling

According to the above assumptions, the mathematical models can be established and derived as follows:

(0) In matrix systems

Considering the pseudo steady diffusion and convection from matrix systems to cleat systems and the gas desorption from the matrix surface, the governing equation in spherical matrix systems can be written based on Eq. (2) [30]:

\[
-\frac{15 k_m \beta_m}{R_m^2 \mu} \rho_0 (p_m - p_f) = \frac{\partial (\rho_m \varphi_m)}{\partial t} + \rho_{sc} \frac{\partial}{\partial t} \left( \frac{V_L p_m}{p_L + p_m} \right)
\] (4)

where \( R_m \) is the spherical radius of matrix elements, \( m \); \( p_f \) is the pressure in a cleat system, MPa.

Substituting the equation of gas state into Eq. (4), the following equation can be obtained:

\[
-\frac{15 k_m \beta_m \rho_0}{R_m^2 \mu} (p_m - p_f) = \varphi_m \frac{c_{gm}}{z} \frac{p_m \partial p_m}{\partial t}
\] + \( \frac{p_{sc} T}{T_{sc}} \frac{V_L p_m}{(p_L + p_m)^2} \frac{\partial p_m}{\partial t}
\] (5)

Due to variation of physical properties of gas with pressure, Ertekin and Sung [20] and King and Ertekin [26] used pseudo-pressure function to simplify the transport mathematical model.

\[
\psi = 2 \int \frac{p}{\mu z} dp
\] (6)

Substituting Eq. (6) into Eq. (5), Eq. (5) can be rewritten as:

\[
-\frac{15}{R^2} \left( \psi - \psi_f \right) = \frac{\varphi_m \mu c_{gm}}{\rho_m \varphi_m \left( p_L + p_m \right)} \frac{\partial \psi_m}{\partial t}
\] (7)

Furthermore, to simplify the derivation, the mathematical model can be derived in dimensionless form. Dimensionless definitions of all variables in the mathematical model proposed in this paper are shown in the Appendix.

With the definitions in the Appendix and the Laplace transform, Eq. (7) can be written in the following form:

\[
\left( 1 - \omega \gamma \right) \frac{\partial \bar{\psi}_{md}}{\partial \lambda} + \lambda \left( \bar{\psi}_{md} - \bar{\psi}_{fd} \right) = 0
\] (8)

where \( z \) is the time in Laplace space, \( \lambda \) is the transfer coefficient from matrix systems to cleat systems; \( \omega \) is the storage coefficient of gas in cleat systems. \( c_{tm} \) is the total compressibility in matrix systems, MPa^-1; \( \gamma \) is the free gas storage coefficient.

\[
\begin{aligned}
\lambda &= 15 \frac{k_m L^2}{k_h R^2} \\
\omega &= \frac{\mu (\varphi_m \varphi_{sc} + \varphi_f \varphi_{sc})}{\varphi_m \varphi_{sc} \varphi_f + \varphi_{sc} \varphi_f} \\
\gamma &= \frac{\varphi_m \varphi_{sc} \varphi_f}{\varphi_{sc} \varphi_f} \\
c_{tm} &= c_{gm} + \frac{\rho_{sc}}{\rho_m \varphi_{sc} (p_L + p_m)^2} \frac{V_L p_m}{(p_L + p_m)^2}
\end{aligned}
\] (9)

where \( k_m \) is the permeability in cleat systems, m^2; \( L \) is the reference length, m.

(0)In cleat systems

Based on the Darcy flow and material balance law, the governing equation in cleat systems can be written as:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho_f p_f \frac{\partial p_f}{\partial r} \right) + \frac{15}{R_m^2} \frac{k_m \beta_m \rho_0}{\mu} (p_m - p_f)
\] (10a)

\[
= \frac{\partial p_f}{\partial t}
\]

where \( r \) is the radial distance, m; \( p_f \) is the gas density in cleat systems; \( p_m \) is the pressure in cleat systems under the reservoir condition, kg/m^3; \( \varphi_f \) is the porosity in cleat systems, decimal.

Using the initial condition:

\[
p_f |_{t=0} = p_i
\] (10b)
In the cleat systems, the inner boundary condition at constant rate production is:

$$\left.\frac{\partial p_f}{\partial r}\right|_{r=r_e} = 0$$  \hspace{1cm} (10d)

where \(q_{sc}\) is the production rate, \(m^3/\text{day}\); \(h\) is the reservoir thickness, \(m\).

The external boundary (closed boundary) is:

$$\left.\frac{\partial p_f}{\partial r}\right|_{r=0} = \frac{q_{sc} \mu B}{2\pi k_p h}$$ \hspace{1cm} (10c)

where \(q_{sc}\) is the production rate, \(m^3/\text{day}\); \(h\) is the reservoir thickness, \(m\).

Furthermore, combined dimensionless definitions with the Laplace transform, Eqs. (10a)–(10d) can be written as:

\[
\frac{\partial^2 \psi_{fD}}{\partial r^2} + \frac{1}{r} \frac{\partial \psi_{fD}}{\partial r} - \lambda \beta z (\psi_{fD} - \bar{\psi}_{mD}) = \omega z \frac{\partial \tilde{\psi}_{fD}}{\partial r} \tag{11a}
\]

Inner boundary:

\[
\lim_{r_0 \to 0} \frac{\partial \bar{\psi}_{fD}}{\partial r} = -\frac{1}{z} \tag{11b}
\]

External boundary:

\[
\frac{\partial \bar{\psi}_{fD}}{\partial r} (r_e, z) = 0 \tag{11c}
\]

Combining Eq. (8) with Eqs. (11a)–(11c), the point source solution of transient pressure response in Laplace space can be obtained.

\[
\bar{\psi}_{fD} (r_D, z) = \frac{1}{z} \left[ K_0 r_D \sqrt{zf(z)} + \frac{K_1 (r_D \sqrt{zf(z)})}{l_1 (r_D \sqrt{zf(z)})} I_0 (r_D \sqrt{zf(z)}) \right] \tag{12}
\]

where \(r_D = \sqrt{x_D^2 + y_D^2}, f(z) = \frac{\lambda D_m \omega (1-\omega_r) z}{\lambda D_m (1-\omega_r) z}\) \((0)\) Flow model of hydraulic fracture

According to the details derivation of a finite conductivity vertical fracture in reservoirs [31, 32], the pressure response of a finite conductivity fractured well in CBM reservoirs in Laplace space can be obtained.

\[
\bar{\psi}_{wD} - \frac{1}{z} \int_0^1 \bar{q}_{fD}(\alpha, z) K_0 (\sqrt{(x_D - \alpha)^2 + y_D^2}) \left[ I_0(\sqrt{zf(z)}) \frac{\sqrt{zf(z)}}{2z \sqrt{zf(z)}} \right] d\alpha \tag{13}
\]

where \(q_{fD} = \frac{1}{z^2} \bar{\psi}_{wD}\)

\[
\bar{q}_{fD} = \frac{1}{z^2} \bar{\psi}_{wD} \tag{16}
\]

where \(q_{fD}\) is the dimensionless rate in Laplace space.

To analyze production data of a fractured well in low permeability and diagnose reservoirs properties, Pratikno et al. [36] developed the production decline type curves
theory, which has been widely used in field production dynamic analysis. The general definition of production decline type curves as given are [9, 36]:

Dimensionless decline rate:
\[
q_{Dd} = q_D b_{Dpss}
\]  
(17)

Dimensionless decline time:
\[
t_{Dd} = \frac{2\pi}{b_{Dpss}} t_{DA}
\]  
(18)

For a well with a finite conductivity vertical fracture, the \( b_{Dpss} \) is a function of \( r_eD \) and \( F_cD \) [36]:
\[
b_{Dpss} = \ln\left(\frac{r_eD}{0.049298 + 0.43464 r_e^2} + a_1 + a_2 u + a_3 u^2 + a_4 u^3 + a_5 u^4 + b_1 u + b_2 u^2 + b_3 u^3 + b_4 u^4\right)
\]  
(19)

where
\[
\begin{align*}
 u &= \ln(F_cD) \\
a_1 &= 0.93626800 \\
b_1 &= -0.38553900 \\
a_2 &= -1.00489000 \\
b_2 &= -0.06988650 \\
a_3 &= 0.31973300 \\
b_3 &= -0.0484653 \\
a_4 &= -0.04235320 \\
b_4 &= -0.00813558 \\
a_5 &= 0.00221799
\end{align*}
\]

Dimensionless rate integral function \( q_{Ddi} \):
\[
q_{Ddi} = \frac{N_pDd}{t_{Dd}} = \frac{1}{t_{Dd}} \int_0^{t_{Dd}} q_{Dd}(a) da
\]  
(20)

Dimensionless rate integral derivative function \( q_{Ddid} \):
\[
q_{Ddid} = -\frac{dq_{Ddi}}{dt_{Dd}} = -t_{Dd} \frac{dq_{Ddi}}{dt_{Dd}}
\]  
(21)

4 Results and discussions

4.1 Model Validation

For this paper, the CBM reservoir is assumed as a dual porosity one which contains cleat systems and matrix systems. If some parameters of Eq. (14) are set to satisfy some conditions, the model proposed in this paper can be converted into other models. If the function \( f(z) = 1 \), this new model can be simplified as a well with a finite conductivity fracture in the homogenous reservoir. To validate our results, the production decline type curves data of the simplified model reported in literature [36] are chosen. Figure 3 shows the comparison results of production decline type curves of a finite conductivity vertical fracture well with \( F_{cd} = 0.1\pi, r_eD = 500 \) and \( s_f = 0 \).

As seen from Figure 3, the type curves of the simplified model show excellent agreement with the work of Pratikno et al. [36]. Therefore, the type curves of the model proposed in this paper are reliable.

4.2 Type curves of a fractured well in CBM reservoirs

Based on the proposed model outlined above, production decline type curves of a finite conductivity vertical fracture well in CBM reservoirs can be obtained by solving Eqs. (16), (17), (20) and (21). To explain the transient transport process of a fractured well in CBM reservoirs more clearly, the following curves are integrated in Figure 4, including type curves of \( q_{Dd}, q_{Ddi}, q_{Ddid}, p_{Di} \) and \( p_{Did} \) versus \( t_{Dd} \). The definition of \( p_{Di} \) and \( p_{Did} \) are given in the Appendix. According to the type curves behavior (Figure 4), six main flow regimes are recognized:

Regime I: linear flow regime (Figure 5a). The curves of dimensionless pressure integral function and dimensionless pressure integral derivative function are two parallel sloping lines. This flow regime represents fluid flowing linearly from the formation into hydraulic fractures and from hydraulic fractures into the wellbore.

Regime II: early radial flow in cleat systems (Figure 5b). The slope of the dimensionless rate integral derivative function is constant, and the slope of dimensionless pressure integral derivative function is zero.
Regime III: interporosity flow regime. Both of the curves of the dimensionless rate integral derivative function and dimensionless pressure integral derivative function are concave, which reflect the transfer of CBM from the matrix system to cleat systems.

Regime IV: the second radial flow (late pseudo radial flow) regime (Figure 5c). The curves of the dimensionless rate and dimensionless rate integral derivative converge to a constant slope line, and the slope of dimensionless pressure integral derivative is zero. This regime indicates that fluid is flowing radially from the formation into the wellbore.

Regime V: transient regime.

Regime VI: boundary dominated flow regime (Figure 5d). The dimensionless decline rate converges to a straight line with \(-1\) slope, while the slope of the dimensionless pressure integral function and pressure integral derivative function is 1.

4.3 Parameter sensitivity analysis

Varying parameters can affect the transient production decline type curves significantly. Therefore, the effect of these parameters on production decline type curves will be discussed in detail.

Figure 6 shows the type curves characteristic of production decline affected by the gas storage coefficient of gas in the cleat ($\omega$). The $\omega$ represents the relative storage capacity of CBM in cleat systems. It can be observed that $\omega$ mainly affects the type curves in regime I–III. Meanwhile a bigger $\omega$ leads to a larger value of type curves and a shallower concavation of dimensionless rate integral derivative function in the interporosity flow regime.

Figure 7 shows the production decline type curves of different transfer coefficient from a matrix to the cleat ($\lambda$). The parameter $\lambda$ reflects the relative flow capacity from matrix systems to cleat systems. As is shown in Figure 6, parameter $\lambda$ has a dominant effect on the interporosity flow (regime III). A larger $\lambda$ means a stronger flow capacity in matrix systems, which results in an earlier emergence time of regime III. When $\lambda$ equals 0.001 in Figure 6, the second radial flow of dimensionless rate integral derivative function curve does not emerge (Figure 7). Therefore, if $\lambda$ is too small, then regime IV will be concealed.
The effect of the modified coefficient of permeability ($\beta_m$) on production decline type curves is nearly the same as that of the storage coefficient of gas in the cleat ($\omega$), but is less significant. As is shown in Figure 6 and Figure 7, the period of regime will be start earlier as $\lambda$ and $\beta_m$ increases. This is because a bigger $\lambda$ and $\beta_m$ will lead to a higher relative flow capacity of matrix systems.

Figure 9 shows that the dimensionless fracture conductivity ($F_{cD}$) has a great effect on regime of production decline type curves. It can be seen that the value of production decline type curves increases with increasing value of $F_{cD}$ during the four regimes. The main reason for this is that the larger $F_{cD}$ is, the smaller the resistance of flow in a hydraulic fracture is. Notably, we can obtain more insight from the detail in Figure 8. As $F_{cD}$ increases from 1 to 10, the improved value of production decline type curves is much less than the one when $F_{cD}$ increases from 10 to 100. In addition, there is an interesting phenomenon that type curves are nearly coincident when $F_{cD} = 100$ and $F_{cD} = 1000$. This is observed when the dimensionless fracture conductivity increases to 100, and the production decline type curves of a finite conductivity vertical fracture well ($F_{cD} = 0.1\pi, r_{eD} = 500, s_f = 0$) is nearly the same as that of an infinite conductivity vertical fracture well. Therefore, when the dimensionless fracture conductivity is more than 100, the fracture can be considered as an infinitely conductive one.

Figure 11 shows the effect of the dimensionless reservoir drainage radius ($r_{eD}$) on production decline type curves. It can be seen that four regimes including linear flow, early radial flow in cleat systems, interporosity flow regime, late pseudo radial flow regime, are governed by $r_{eD}$. In addition, the value of type curves increases with a decrease in the value of $r_{eD}$ during the four regimes.

According to the results discussed above, the production decline type curves for CBM reservoirs in this work...
provides a useful tool for analysis of actual field production data of a fractured well in CBM reservoirs.

5 Conclusions

This paper investigates the production decline type curves of a finite conductivity fracture well in CBM reservoirs, and analyzes the effects of the characteristic parameters. The main conclusions can be drawn:

1. A novel production decline type curves analysis model of a finite conductivity fractured well in CBM reservoirs, which considers the pseudo steady diffusion and convection from matrix systems to cleat systems, is established.
2. Standard production decline type curves are plotted, and divided into six regimes including linear flow regime, early radial flow in cleat systems, interporosity flow regime, the second radial flow regime, transient regime, and boundary dominated flow regime.
3. The effects of five parameters $\omega$, $\lambda$, $\beta_m$, $r_{ed}$, and $F_{CD}$ on production decline type curves are analyzed in detail. The results show the following: A bigger $\omega$ leads to a shallower concavation of dimensionless rate integral derivative function in interporosity flow regime. The period of interporosity flow regime will start earlier as $\lambda$ and $\beta_m$ increases. During linear flow, early radial flow in cleat systems, interporosity flow regime, and late pseudo radial flow regime, the value of production decline type curves increases with a decrease in $r_{ed}$ while the value of type curves increases with an increase in $F_{CD}$.

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Appendix

Dimensionless radial distance in the matrix system:

$$r^{\text{mD}} = \frac{r}{R_m}$$

Dimensionless radius:

$$r^{\text{D}} = \frac{r}{x_f}$$

Dimensionless reservoir drainage radius:

$$r^{\text{eD}} = \frac{r_e}{x_f}$$

Dimensionless x distance:

$$x^{\text{D}} = \frac{x}{x_f}$$

Dimensionless y distance:

$$y^{\text{D}} = \frac{y}{y_f}$$

Dimensionless time (A):

$$t^{\text{DA}} = \frac{k_f t}{\mu (\varphi_m c_{gm} + \varphi_f c_{gf}) A^2}$$

Dimensionless time (x_f):

$$t^{\text{D}} = \frac{k_f t}{\mu (\varphi_m c_{gm} + \varphi_f c_{gf}) x_f^2}$$

Dimensionless pressure in cleat systems:

$$\psi_f^{\text{D}} = \frac{\pi k_f h T_{sc}}{P_{sc} q_{sc} T} (\psi_f - \psi_f)$$

Dimensionless pressure in matrix systems:

$$\psi_{mD} = \frac{\pi k_f h T_{sc}}{P_{sc} q_{sc} T} (\psi_m - \psi_m)$$
Dimensionless fracture conductivity:

\[ F_{cD} = \frac{k_f W}{k_{f_h} x_f} \]

Dimensionless production rate of the fracture:

\[ q_{fD} = \frac{q_f}{q_{sc}} \]

Dimensionless pressure integral function:

\[ p_{Di} = \frac{1}{t_{Da}} \int_0^{t_{oa}} p(t) dt_{Da} \]

Dimensionless pressure integral derivative function:

\[ p_{Di,d} = \frac{d p_{Di}}{d \ln t_{Da}} = t_{Da} \frac{d p_{Di}}{dt_{Da}} \]