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Flowing Material Balance and Rate-Transient Analysis of Horizontal Wells in Under-Saturated Coal Seam Gas Reservoirs: A Case Study from the Qinshui Basin, China

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Abstract: Two phase flow and horizontal well completion pose additional challenges for rate-transient analysis (RTA) techniques in under-saturated coal seam gas (CSG) reservoirs. To better obtain reservoir parameters, a practical workflow for the two phase RTA technique is presented to extract reservoir information by the analysis of production data of a horizontal well in an under-saturated CSG reservoir. This workflow includes a flowing material balance (FMB) technique and an improved form of two phase (water + gas) RTA. At production stage of a horizontal well in under-saturated CSG reservoirs, a FMB technique was developed to extract original water in-place (OWIP) and horizontal permeability. This FMB technique involves the application of an appropriate productivity equation representing the relative position of the horizontal well in the drainage area. Then, two phase (water + gas) RTA of a horizontal well was also investigated by introducing the concept of the area of influence (AI), which enables the calculation of the water saturation during the transient formation linear flow. Finally, simulation and field examples are presented to validate and demonstrate the application of the proposed techniques. Simulation results indicate that the proposed FMB technique accurately predicts OWIP and coal permeability when an appropriate productivity equation is selected. The field application of the proposed methods is demonstrated by analysis of production data of a horizontal CSG well in the Qinshui Basin, China.

Keywords: Two phase flow; rate-transient analysis; flowing material balance; coal seam gas; horizontal well

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1. Introduction

Hydraulic fracturing and horizontal well completion are effective approaches to stimulate reservoirs, and enhance well productivity in coal seam gas (CSG) reservoirs, respectively [1–3]. An effective tool to estimate reservoir and stimulation information of horizontal wells is the modern production data analysis (PDA), including rate-transient analysis (RTA) and flowing material balance (FMB) techniques. Both techniques are powerful methods for reservoir characterization in unconventional reservoirs, such as tight gas, shale gas, and dry CSG reservoirs, when single-phase flow occurs [4–6]. In the production data analysis (single-phase flow), a diagnostic curve is plotted using rate-normalized pressure (RNP) and pseudo-time to identify the flow regimes [7–9]. Then, reservoir and stimulation properties, including original gas-in-place (OGIP), permeability, skin factor, and hydraulic fracture characteristics (length and conductivity), can be extracted in each flow regime using specialized straight-line plots. For CSG reservoirs, material balance pseudo-time and superposition time are employed in RTA studies due to the change in the bottom hole pressure and the production rate [1,9]. The gas desorption impact on pressure is also considered in material balance pseudo-time using desorption compressibility, which is included in the total compressibility as an independent term [10,11].

The RTA of a multi-staged hydraulically fractured horizontal well is complicated and may require additional information, such as a micro-seismic interpretation, to obtain promising results [1,2,12,13]. The production history (recorded on a daily basis) of a typical horizontal well may exhibit five flow regimes, namely, early radial, formation linear, elliptical, pseudo-radial, and boundary-dominated flow regimes [1]. In unconventional reservoirs, including tight gas, shale gas, and CSG reservoirs, the horizontal interval of the well should be long enough to enhance well productivity and, hence, rectangular drainage areas are common [14–18]. Early radial, formation linear, and boundary-dominated flow regimes can generally be captured in horizontal wells because the horizontal interval penetrates most part of the drainage area, thereby eliminating elliptical and pseudo-radial flow regimes.

The RTA methods for a horizontal well in dry CSG reservoirs utilize analytical solutions developed for single-phase flow in tight and shale gas reservoirs [2,15,19]. A summary of flow regime analysis for a horizontal well in dry CSG reservoirs is shown in Table 1 [1,3,20].

Table 1. Summary of flow analysis for a horizontal well in dry CSG reservoirs.

Flow Regimes	Log-Log Diagnostic	Straight Line Plot	Extracted Properties
Early radial flow	Zero slope	RNP_g vs. $\text{Log} t_{ca}$ or $t_{ca,rsp}$	$\sqrt{k_y k_z} = \frac{1637T}{mL_w}$ $\sqrt{k_y} = \frac{576.56T f_{cp}^*}{mhL_w \sqrt{\phi \mu_g c_i^*}}, \text{ OGIP} = f_{cp}^* \frac{200S_{gi} \sqrt{t_{dhs}}}{m\phi B_{gi} c_i^*}$ $G_i = -\frac{b}{m}$
Linear flow	Half slope	RNP_g vs. $t_{ca}^{0.5}$ or $t_{ca,isp}$	
Boundary-dominated flow	Unit slope	$\frac{1}{RNP_g}$ vs. $\frac{G_i[m(p_i)-m(p_R)]}{[m(p_i)-m(p_{wf})]}$	

In under-saturated CSG reservoirs, the fracture system is generally saturated with water and more than 90% of gas is in the sorption phase at the initial reservoir conditions [21–25]. Hence, the production generally starts with single-phase (water) flow. Yarmohammadtooski [26] utilized early water production data of a dewatering vertical well in the Fairview Field, eastern Australia, to measure original water-in-place (OWIP) and absolute permeability of the Bandanna Coal Formation using FMB methods. Shahamat and Clarkson (2017) calculated original oil-in-place (OOIP) for a multi-fractured horizontal well using a multi-well, multi-phase flowing material balance method; however, permeability of the reservoir was not calculated.

When production enters the two phase (water + gas) flow stage, the current studies of RTA in under-saturated CSG reservoirs mainly refer to the study of two phase (oil + solution gas) flow or two phase (gas + condensate oil) flow in tight and shale reservoirs [14,18,27]. Previous studies have shown that two phase flow in transient flow regimes presents significant challenges to RTA application in CSG reservoirs, leading to the incorrect identification of flow regimes and inaccurate extraction of reservoir information [8,12,28,29]. Following empirical correction methods in transient linear flow [15], Qanbari and Clarkson [17] proposed an analytical correction factor (f_{cp}^*) for a formation linear flow regime to study two phase (gas + oil) RTA with stress-dependent permeability using an iterative integral approach. This correction factor (f_{cp}^*) can dramatically increase the accuracy. To simplify multi-phase flow RTA in tight reservoirs, Mohan [30] introduced the total equivalent production rate to replace the primary fluid rate for RTA in transient and boundary-dominated flow regimes. To overcome the two phase problem for RTA in CSG reservoirs, Qanbari and Clarkson [14] introduced the concept of contacted water-in-place (CWIP) and the dynamic drainage area (DDA), and proposed a workflow for the analysis of formation linear flow regimes inspired by the method used in tight and shale reservoirs [17,31]. For the DDA in undersaturated CSG reservoirs, water production data was employed to calculate the investigation distance in formation linear flow regimes [20]. Because the DDA is calculated using pressure data, the DDA in under-saturated CSG reservoirs include both a two phase (gas + water) flow zone and a single-phase water flow zone.

The application of the DDA results in underestimation of water saturation in the DDA, which consequently results in gas relative permeability values that are lower than the actual values. In our previous study [32], the concept of the area of influence (AI) was presented to obtain the average water saturation in formation linear flow regimes. It was shown that the application of the AI can result in more accurate estimation of hydraulic fracture half-length in transient linear flow regimes. Nevertheless, the approach in the previous study [32] was developed for the transient linear flow regime of a vertical well stimulated with a single hydraulic fracture.

In this paper, we develop a workflow for two phase RTA to estimate reservoir information extracted from the production profile of a horizontal well. The results from the proposed FMB method (single-phase water flow) allows crosschecking with the results obtained from two phase (water + gas) RTA of existing flow regimes (e.g., formation linear flow and boundary-dominated flow) when the concept of the AI is applied. Simulation and field examples are presented to demonstrate the application of the proposed FMB, the concept of the AI, and the two phase workflow.

2. Study Area and Wellbore Description

The commercial production of CSG in China started in the late 1980s, with total OGIP estimated to be 1298.65 Tscf in shallow coalbeds (depth < 6561 ft) [33,34]. The Qinshui Basin is located in the mid-eastern area of China, and covers an area of 23.49×10^3 km² (Figure 1). The Qinshui Basin is a NNE (north-north-east) large-scale synclinorium, and the long axis of the Qinshui Basin has a length of approximately 330 km and a northeast-southwest direction [33,35]. The CSG wells in China have increased significantly from 1183 to 12,547 during the period of 2006 to 2012, and approximately 40% of these wells were drilled in the Qinshui Basin. By the end of 2014, the CSG demonstration production zone was established in the Qinshui Basin, accounting for 71% of the total number of producing wells, 65% of the proven OGIP of CSG, and 81% of the yearly production in China [36].

The study area is located in the Panzhuang production block, which is one of the main CSG production blocks in the Qinshui Basin [37,38]. The Panzhuang block is located at the southern edge of the Qinshui Basin (Figure 1) and the target coal is seam No.3, which is located in the middle and lower parts of Shanxi Formation [39]. The thickness of coal seam No.3 ranges from 14.59 ft to 28.71 ft. In the Panzhuang block, coal seam No.3 is separated from the upper sandstone K8 by siltstone, carbonaceous mudstone, and mudstone. Coal seam No.3 is the target seam for CSG production in the Qinshui Basin [40] and the present burial depth of coal seam No.3 ranges from 1012 ft to 4593 ft. The coal rank is anthracite in the study area, with an average R_{max} of 3.78% [41]. Coal seam No.3 has high adsorption capacity, with Langmuir volume on a DAF (dry-ash free) basis ranging from 938 to 1585 Scf/ton, mostly between 1059 and 1412 Scf/ton, and, on average, 1307 Scf/ton. The gas content of coal seam No.3 in the study area ranges from 282 to 741 Scf/ton [42]. Gas and water production rates vary significantly in each production block of the Qinshui Basin [35,43], with the dewatering stage ranging from only one week to a few months in the Panzhuang production block.

The target well was completed in coal seam No.3 using the horizontal well technique. The wellbore schematic is given in Figure 1. Surface casings (13-3/8 inch) were set at the vertical depth of 459 ft and the intermediate casing (9-5/8 inch) was placed at the vertical depth of 1653 ft. The 5-1/2 inch production casing was run in the horizontal section of the wellbore (at the true vertical depth of 1857 ft). The effective production interval of this horizontal well is approximately 8960 ft.

Figure 1. The study area and target horizontal well in the Panzhuang block.

3. Methodology

3.1. Flowing Material Balance for a Horizontal Well in an Undersaturated CSG Reservoir (Single-Phase Water)

In under-saturated CSG reservoirs, during the dewatering process (single-phase flow), boundary effects may easily dominate the flow. In the boundary-dominated flow regime, using the FMB method, the drainage area and absolute permeability of a vertical well can be extracted. To extract the permeability of a horizontal well, an appropriate equation should be employed.

The general FMB equation for single-phase flow (water) is given by Equation (1). In the general form, b_{pss} accounts for the pressure loss due to the pseudo-steady state inflow of fluid (see Appendix A).

$$\frac{q_w}{\Delta p} = -\frac{W_p B_w}{\Delta p c_t} \frac{1}{N_w b_{pss}} + \frac{1}{b_{pss}} \quad (1)$$

When b_{pss} is obtained using the straight-line form of Equation (1), the permeability of the reservoir can be extracted using b_{pss} . For a stimulated vertical well, the productivity equation with equivalent skin factor can be used in the FMB method [26,32]. However, for a horizontal well, the same productivity equation could lead to errors. In this section, we derive a new form of FMB to analyze the early single-phase water production rates using different productivity equations.

The relative position of the horizontal well in the drainage area may result in the development of an elliptical flow regime followed by a boundary-dominated flow regime. In this case, the productivity of the horizontal well can be estimated using the Joshi equation (see Appendix A) and, hence, b_{pss} takes the following form:

$$b_{pss} = \frac{141.2(\mu_w B_w) \left[\ln \frac{a + \sqrt{a^2 - (L_w/2)^2}}{L_w/2} \right]}{k_y h} \quad (2)$$

where a is the major axis of the elliptical drainage area and can be calculated using the equivalent drainage radius (r_e) and the length of horizontal interval (L_w), shown as:

$$a = (L_w/2) \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{(L_w/2r_e)^4}} \right]^{0.5} \quad (3)$$

The relative position of the horizontal well in the drainage area can also result in formation linear flow followed by boundary-dominated flow, particularly in long horizontal wells. For example, the relative position of our study well, with respect to the nearby wells in the Qinshui Basin and its long horizontal interval (8960 ft), fits in this category. In this case, the productivity of the horizontal well can be calculated using the Clarkson equation [28]. Then, the expression of b_{pss} can be written as:

$$b_{pss} = \frac{141.2(\mu_w B_w) \left(\frac{2\pi y_d}{L_w} \right)}{k_y h} \quad (4)$$

The detailed derivation of the FMB equations using both Joshi and Clarkson's productivity equations are shown in Appendix A. Simulation examples are employed below to demonstrate how coal permeability is obtained using the proposed FMB equations.

3.2. Water Saturation Calculation in the Area of Influence (AI)

When dewatering reduces the reservoir pressure to a critical value, the gas begins to desorb and flows in the cleats and fractures of the coal. This pressure value is named the critical desorption pressure, which is an important value to separate the boundary

between single-phase water flow and two phase flow in coal. After the single-phase (water) production stage, the two phase (water + gas) production begins for a horizontal well in an under-saturated CSG reservoir.

For two phase RTA, water saturation is the key factor to extract reservoir information. To calculate the correct water saturation, which is used to determine gas relative permeability for correcting the RNP, the area of influence (AI) is introduced as the area where gas desorption and flow occurs. Unlike the dynamics drainage area (DDA) [20,44], the AI in an under-saturated CSG reservoir is the actual area of the two phase flow zone. Hence, in transient flow regimes, the AI in an under-saturated CSG reservoir is smaller than the DDA and, as a result, average water saturation in the AI provides more accurate results for the purpose of two phase RTA. In our previous study [32], we showed that the application of the AI in the analysis of formation linear flow of a hydraulically fractured CSG well (vertical) resulted in a more accurate estimation of the fracture half-length compared to the DDA.

In this paper, we introduce the AI for both early radial flow and formation linear flow regimes for a horizontal well in an under-saturated CSG reservoir. Because the early radial flow regime occurs quickly, the impacts of pressure on rock and fluid properties may be ignored. The average water saturation in the AI of early radial flow regime can be approximately obtained using the water saturation in the cylinder around the horizontal interval (Equation (5)), where L_w is the length of the horizontal interval and the half thickness of the coal seam ($h/2$) is the radius of the cylinder. With the average water saturation in AI of early radial flow, the geometric-average permeability can be estimated using two phase RTA methods (Appendix B).

$$s_w = \frac{B_w(W_p - W_e)}{1939.5\pi L_w h^2 \phi_i} \quad (5)$$

In a transient formation linear flow regime, the average water saturation in the AI is calculated using gas production data to represent the two phase flow in the area of influence. Figure 2 shows the pressure distribution of formation linear flow for a horizontal well in a coal seam. The critical desorption pressure separates the single water flow and the two phase flow in the coal. The area of influence and the dynamic drainage area are shown separately in Figure 2 as the formation linear flow propagates. Because the AI is smaller than the DDA, the average water saturation in the DDA may be overestimated.

Figure 2. The AI and DDA of the transient formation linear flow regime of a horizontal well in an under-saturated CSG reservoir.

Inspired by the calculation of the DDA [44], an iterative process for average pressure and average water saturation in the AI of a transient formation linear flow regime is pro-

posed for under-saturated CSG reservoirs. This iterative process combines the calculation of the AI and the material balance method. The detailed iterative process can be seen in our previous study [32]. The calculation of average pressure and average water saturation in transient linear flow regimes requires simultaneously solving four equations. For the transient linear flow regime, the gas production rate of a horizontal well [44] can be expressed as:

$$q_g = \frac{k_y h \bar{k}_{rg} \left[m(\bar{p}_{AI}) - m(p_{wf}) \right]}{1424 T \left[\frac{4}{\pi} \left(\frac{y_{AI}}{L_w} \right) \right]} \quad (6)$$

where y_{AI} is the distance of the AI in the transient linear flow regime (Qanbari and Clarkson 2013a), which can be expressed by:

$$y_{AI} = \delta \sqrt{\frac{k_y t}{(\varphi \mu_g c_t^*)_i}} \quad (7)$$

Under the constant bottom-hole flowing pressure condition, $\delta = 0.159$. This coefficient depends on the operational conditions (rate and flowing bottom-hole pressure). In this work, $\delta = 0.159$ is used for all examples and practice has indicated that the extracted results are not highly sensitive to this coefficient [14,20,44,45].

For formation linear flow, the material balance equation is derived to calculate the average water saturation and pressure in the area of influence. In the AI of an under-saturated CSG reservoir, gas desorbs, leading to gas production. Hence, the cumulative gas production (G_p) is equal to the decline in the gas content in the AI of formation linear flow, which propagates with time. The decrease in gas content can be expressed by the change in gas saturation and sorption capacity. The expanding AI is a function of the length of the horizontal interval (L_w) and the distance of the AI (y_{AI}). Therefore, a form of material balance equation can be developed in this scenario, as given by (Equation (8)):

$$G_p = 2L_w y_{AI} h \left[\left(\frac{V_L p_{cd}}{p_L + p_{cd}} \right) - \left(\frac{\varphi S_g}{B_g} \right)_{\bar{p}_{AI}} + \frac{V_L \bar{p}_{AI}}{p_L + b \bar{p}_{AI}} \right] \quad (8)$$

To obtain the average pressure in the area of influence, the average water saturation in the AI of transient formation linear flow is required, which can be expressed by:

$$s_w = 1 - \frac{B_w(W_p - W_e)}{7758.4 y_{AI} L_w h \varphi_i} \quad (9)$$

The simultaneous solutions for Equations (6)–(9) require the iterative method, which is accomplished by trial and error. The details of this iterative method are given in the workflow and can be seen in our previous study [32]. After obtaining the average pressure and average water saturation in the AI of the transient formation linear flow regime, the single-phase RNP is corrected using relative permeability values, and the coal permeability can be extracted using the slope of $k_{rg} \times RNP_g$ versus $t_{ca}^{0.5}$ (or superposition time $t_{ca,ls}$).

When the transient formation linear flow ends and the boundary effects start to dominate the flow, the OGIP can also be extracted using the formation linear flow regime. Once the end of formation linear flow (t_{ehs}) is observed, the distance of the AI (y_{AI}) can be used to calculate the drainage area of the horizontal well. Then, OGIP can be obtained using the drainage area and gas content of the coal using Equation (10):

$$OGIP = 2L_w y_{AI} h \times V_{coal} = 2\delta h L_w V_{coal} \sqrt{\frac{k_y t_{ehs}}{(\varphi \mu_g c_t^*)_i}} \quad (10)$$

Appendix B summarizes the equations and the procedure to perform two phase RTA for a horizontal well, which were previously developed by other authors [1,6,32] when boundary-dominated flow is observed.

3.3. Workflow for Two phase RTA in Horizontal Well

To show two phase RTA for a horizontal well in under-saturated CSG reservoirs, a practical workflow is presented to combine both FMB for the dewatering stage and RTA for two phase flow. The combination allows rigorous crosschecks to be undertaken and can precisely extract reservoir properties. Figure 3 illustrates the sequential procedures in the workflow to extract reservoir information using both single-phase (water) FMB and two phase RTA for the simulation and field examples presented in this work. The early water production is analyzed using the proposed FMB method. The average water saturation in the AI, calculated using our proposed method, is applied to correct the RNP for two phase RTA. The workflow follows the following steps:

- (1) The gas rates, water rates, bottom-hole pressure, well completion type, and core analysis should be subsequently collected for the analysis. In addition, other necessary information includes the possible drainage area from the location of wells, gas content, isothermal sorption curve, porosity of cleat, and coal absolute permeability and relative permeability from laboratory tests. A data quality check is necessary, and RNP and t_{ca} are then calculated using gas production rates and flowing bottom-hole pressures.
- (2) The proposed FMB method is used to first identify the boundary-dominated flow regime and, second, to extract the OWIP and horizontal permeability using the early single-phase water production rates. Note that OWIP, obtained in this step, and the water production history, can be utilized to determine average water saturation for two phase RTA.
- (3) Average water saturation is used to correct RNP to construct a diagnostic plot to distinguish available flow regimes, such as early radial flow, formation linear flow, and boundary-dominated flow regimes. Note that, when RNP* is corrected using average water saturation, and calculated using the whole drainage area rather than the area of influence, the slopes of early radial flow and boundary-dominated flow regimes in the diagnostic plot are not exactly equal to 0 and 1, respectively. However, it is possible to identify the early radial flow and boundary-dominated flow regimes due to their distinguishing slopes. This will be demonstrated using simulation examples in next section.
- (4) For early radial flow regime, the average water saturation in the AI can be approximated using Equation (5) and the geometric-average permeability is calculated using the slope of $k_{rg} \times \text{RNP}_g$ versus $\log t_{ca}$ (or superposition time $t_{ca,rsp}$, see Appendix B).
- (5) For transient formation linear flow, a value for horizontal permeability (k_y) is initially assumed and the dynamic distance of the AI is calculated using Equation (7). Then, an initial value for the average pressure in the AI ($\bar{p}_{AI}$) is estimated using Equation (6). Based on the initial value of $\bar{p}_{AI}$, the average water saturation and average pressure in the AI are calculated using the trial-and-error method of the material balance equation (Equations (8) and (9)). Finally, the average pressure and average water saturation are utilized to construct the straight-line plot. The square root of horizontal permeability ($\sqrt{k_y}$) can be extracted using the slope of $k_{rg} \times \text{RNP}_g$ versus $t_{ca}^{0.5}$. The calculated k_y is compared with the assumed permeability. This process continues until the calculated value converges. Once the calculation converges and k_y is obtained, the vertical permeability (k_z) may be calculated using the geometric-average permeability ($\sqrt{k_y k_z}$), obtained from the early radial flow regime. When the transient formation linear flow regime ends, the end time of linear flow (t_{els}) can be approximated from the plot of RNP* versus $t_{ca}^{0.5}$. This end time assists in the estimation of the total drainage area, which can be used to estimate OGIP when coal gas content is known (see (Equation (10))). The horizontal permeability extracted from formation linear

flow should be in agreement with the value from the single-phase FMB method. This provides a valuable option for crosschecking.

- (6) For the boundary-dominated flow regime, the material balance equations are well developed (see Appendix B), and can be applied to calculate the average reservoir pressure and water saturation. The OGIP can be obtained using the relationship and equations listed in Table 1, and the results should be consistent with the results calculated using other flow regimes (e.g., formation linear flow and early radial flow regimes).

Figure 3. Generalized workflow for two phase RTA of a horizontal well in an under-saturated CSG reservoir.

4. Results and Analysis

Both simulation and field examples are presented to validate the proposed single-phase (water) FMB and the application of the AI in the two phase (water + gas) RTA technique for horizontal wells in under-saturated CSG reservoirs. In the simulation ex-

amples, the single-phase (water) FMB is applied to verify the appropriate productivity equations in Section 3.1 and the two phase RTA study is conducted to test the workflow in Section 3.3. The field example is studied using the proposed workflow to extract coal permeability. The details of simulation and field examples are provided as follows:

Simulation example for single-phase (water) flow:

- Permeability ($k_x = k_y = 2$ mD, $k_z = 1$ mD) and $s_w = 100.0\%$;
- Horizontal well with no hydraulic fractures; Simulation example for two phase (water + gas) flow in under-saturated coal seam:
- Permeability ($k_x = k_y = 2$ mD, $k_z = 1$ mD) and $s_w = 100.0\%$;
- Horizontal well with no hydraulic fractures;
- The length of the horizontal interval is 8400 ft and almost penetrates the whole drainage area. Field example for two phase flow in the Qinshui Basin, China:
- Coal with 100% initial water saturation, average permeability 2.47 mD, and 2.5 years production history;
- Horizontal well with no hydraulic fractures;
- Horizontal interval is 8960 ft and almost penetrates the entire drainage area.

4.1. Simulation Example

The gas and water production profile of simulation examples were generated using CBM-module in the ECLIPSE 2011. The model assumptions include:

- (1) Dual porosity model;
- (2) Gas desorption is described by the Langmuir isotherm and gas diffusion follows Fick's law;
- (3) Two phase flow in the coal fracture is modelled using the Darcy law;
- (4) Isothermal condition;
- (5) Methane is the only component in the model;
- (6) The pressure difference in the horizontal interval can be ignored and bottom-hole pressure along the horizontal interval is the same.

Figure 4 shows the five simulation models for a horizontal well located in the drainage area for the simulation of single-phase (water) flow. Note that the relative position of the horizontal well in the drainage area results in the formation of different flow regimes in each model. The well and reservoir properties are listed in Table 2. Most of the reservoir parameters are based on the data from the Panzhuang production block in the Qinshui Basin, China.

In models 1 to 3, the horizontal interval almost penetrates the entire drainage area, resulting in the formation linear flow regime followed by the boundary-dominated flow regime. In models 4 and 5, elliptical and pseudo-radial flow regimes are formed and followed by the boundary-dominated flow regime. This difference results in using different productivity equations. To test the permeability extracted using Joshi and Clarkson equations, models 1 to 5 are employed to test the proposed single-phase (water) FMB equations for the horizontal well. Model 2 is used to study the two phase (water + gas) RTA method because the horizontal length and drainage area are close to those of our field case.

To generate the production history, the production constraints are set as an initial surface water production rate of 44 Stb/d and a minimum bottom-hole pressure of 50 psi, which are similar to the conditions in the field example. The relative permeability curves and sorption isotherm for simulation purposes are given in Figure 5.

The isothermal sorption data comes from the laboratory test from coal seam No.3 in the Qinshui Basin.

Figure 4. The schematic of a horizontal well located in the drainage area. Note that the relative position of the horizontal well in the drainage area is different in each model.

Table 2. Reservoir properties for the horizontal well in simulation examples.

Model	Shape Parameters		
	L_x , ft	y_d , ft	L_w , ft
Model 1	5740	923	5740
Model 2	8800	923	8400
Model 3	4920	923	3936
Model 4	1968	923	1312
Model 5	1968	923	984
Formation parameters			Value
Thickness of coal, ft			22.38
Cleat porosity, %			1.00
Horizontal permeability of coal, mD			2.00
Vertical cleat permeability of coal, mD			1.00
Coal density, g/cm ³			1.50
Gas content, Scf/ton			431.84
Initial pressure, psi			580.16
Temperature, °F			94
Langmuir pressure, psi			335.1
Langmuir volume, Scf/ton			1322.751
Cleat compressibility, Psi ⁻¹			0.0001
Water compressibility, Psi ⁻¹			3.2×10^{-6}
Initial gas viscosity, cp			0.0153
Well radius, ft			0.1968

Figure 5. Parameters of (a) relative permeability curves and (b) Langmuir isotherm in simulation example.

4.1.1. Single-Phase (Water) FMB for the Horizontal Well

To test the single-phase (water) FMB of a horizontal well, models 1 to 5 are used to generate the water production history. In model 1, the linear flow dominates the flow in the horizontal direction. Due to the relative position of the horizontal interval with respect to the drainage area, the formation linear flow regime becomes less apparent from model 1 to model 5. Equations (2) and (4) are utilized to extract the horizontal permeability. The permeabilities extracted for models 1 to 5 are shown in Table 3.

Table 3. Extracted permeability of the simulation example using single-phase (water) FMB.

Calculated Value	Model 1	Model 2	Model 3	Model 4	Model 5
Using Joshi equation	$k_y = 1.01$	$k_y = 1.91$	$k_y = 2.02$	$k_y = 1.48$	$k_y = 0.93$
Using Clarkson equation	$k_y = 2.03$	$k_y = 2.13$	$k_y = 2.17$	$k_y = 2.52$	$k_y = 3.22$

As shown in Table 3, when the Clarkson productivity equation is utilized in the proposed FMB method, it provides an accurate estimation of horizontal permeability in model 1. This is because the Clarkson productivity equation was developed for a rectangular drainage area, which is close to that of model 1. In addition, for model 1, the boundary-dominated flow directly follows the formation linear flow. Hence, the productivity equation based on linear flow (Clarkson equation) can extract the permeability with a small error.

The Joshi equation, which was developed for a horizontal well in an elliptical drainage area, provides accurate estimations of horizontal permeability in models 2 and 3. This is because the elliptical flow exists in models 2 and 3. For models 4 and 5, the pseudo-radial flow occurs prior to the boundary-dominated flow rather than the elliptical regime. This also leads to large errors in the extracted permeability from the Joshi equation in models 1, 4, and 5.

When the Clarkson productivity equation is utilized in the proposed FMB methods, the accuracy of estimation decreases from model 1 to model 5. Our proposed FMB method well predicts horizontal permeability in models 2 and 3 using both Joshi and Clarkson productivity equations.

4.1.2. Two phase (Water + Gas) RTA for the Horizontal Well in an Under-Saturated Coal Seam Gas Reservoir

Figure 6 shows the gas and water production rate for the simulation example (model 2). To perform two phase RTA, flow regimes should be first identified, and the average water saturation values in the AI can then be calculated using the proposed method. The average water saturation, which represents water saturation in the area of influence, is employed to modify the RNP using the gas relative permeability values.

Figure 6. Simulated production rate of a horizontal well in an under-saturated CSG reservoir.

Following the workflow in Figure 3, the average water saturation can be calculated using the water production history and OWIP, which is calculated using the single-phase (water) FMB method. Note that RNP^* is not calculated using average water saturation in the corresponding flow regime; hence, slopes of early radial and formation linear flow regimes on the diagnostic plot are not exactly equal to 0 and 0.5, respectively. However, flow regimes can still be identified using their distinguishing slopes, as shown in Figure 7a.

Figure 7. The two phase RTA of the simulated horizontal well in an under-saturated coal seam gas reservoir including (a) diagnostic plot, (b) early radial flow regime, (c) transient formation linear flow regime, and (d) boundary-dominated flow regime.

Following the recognition of the flow regimes in Figure 7a, the production data in each regime is selected to calculate the average water saturation in the AI, and the straight-line technique is employed to extract reservoir properties using the plot of $k_{rg} \times RNP_g$ versus t_{ca} . For the simulation case, production data does not change rapidly, and the material balance pseudo-time (t_{ca}) can be used instead of superposition time. In the early radial flow regime, the average water saturation is obtained using Equation (5).

Due to the good data quality of simulated water and gas rates, the geometric-average permeability of coal is also extracted using gas production data (Figure 7b). In the transient formation linear flow regime, average water saturation and average pressure are calculated using our presented method, as described in the workflow (Figure 3). Then both horizontal permeability and OGIP are calculated using the straight-line slopes in the transient formation linear flow regime (Figure 7c). In the boundary-dominated flow regime, the average water saturation and average pressure can be obtained using common material balance equations, and the OGIP is extracted from the slope and the y-intercept of the straight-line

in Figure 7d. The results for geometric average permeability, horizontal permeability, and OGIP obtained from different flow regimes, and the relative errors, are listed in Table 4.

Table 4. Extracted properties * and relative errors of simulation examples using two phase (water + gas) RTA.

Calculated Value	Flow Regime			
	Early Radial Flow	Linear		Boundary-Dominated
Extracted properties	$k_y k_z = 2.01$	$k_y = 2.02$	OGIP = 3536.15	OGIP = 3300.87
Actual properties	$k_y k_z = 2.00$	$k_y = 2.00$	OGIP = 3316.57	OGIP = 3316.57
Relative error	0.50%	1.00%	6.62%	0.47%

* Note that the units of permeability and OGIP are mD and MMScf, respectively.

Table 4 indicates that the horizontal coal permeability (k_y) is obtained with errors lower than 5.0% using the approach proposed in this study. The geometric-average permeability, calculated in the early radial flow regime, is in good agreement with the input values. In addition, the results also suggest that the OGIP calculated from the boundary-dominated flow regime is more reliable than the that extracted from the transient linear flow regime.

Note that the calculated reservoir properties are in good agreement with the actual parameters, indicating that the proposed method for determination of average water saturation in the AI is a practical approach. In the simulation case study, we do not perform a crosscheck because the properties obtained from the simulation case show good consistency. However, the crosscheck is still an important step for the field case. In the next section, the proposed approach is employed to extract the reservoir properties of a field example located in the Qinshui Basin, China.

4.2. Field Example

The field case is based on a horizontal well in the Panzhuang production block, for which the geological and production information are introduced in Section 2. The horizontal well specification and reservoir parameters that we collected are listed in Table 5. The gas and water production history for a period of 30 months, in addition to the bottom-hole flowing pressure data, are shown in Figure 8. As mentioned in the simulation example, because the main fluid is gas in the two phase flow stage, the pressure gradient of the gas along the wellbore is always very small when the production rate is no more than 2.5 MMScf. Hence, we can still assume that the fluid pressure along the horizontal interval is constant in the field case.

Table 5. Reservoir properties * for the target well in the Qinshui Basin, China.

Parameter	Value
Length of horizontal interval, ft	8960
Thickness of coal, ft	22.38
Cleat porosity, %	0.43
Cleat permeability, mD	2.47
Coal density, g/cm ³	1.50
Gas content, scf/ton	459.03
Initial pressure, psi	610.16
Temperature, °F	94
Langmuir pressure, psi	362.60
Langmuir volume, Scf/ton	1362.751
Cleat compressibility, Psi ^{−1}	0.0001
Water compressibility, Psi ^{−1}	3.2×10^{-6}
Initial gas viscosity, cp	0.0153
Well radius, ft	0.1968
Skin, dimensionless	0

* Taken from the well completion report and core analysis.

Figure 8. The gas and water production history of the field case: (a) water and gas production rate and (b) bottom-hole flowing pressure.

As shown in Figure 8, initially, water production is relatively constant at 40 Stb/d for a short period and declines thereafter. The bottom-hole pressure follows a straight line in the early production stage, indicating that the boundary effect dominated the single-phase water production.

For the relative location of the horizontal well in a rectangle area, our targeted well is very close to the shape of model 2. The approach proposed in this paper is utilized to extract the drainage area and horizontal permeability. Figure 9 shows the single-phase (water) FMB plots, including the diagnostic plot and the straight-line plot for the single-phase (water) FMB of the field example. The reservoir and wellbore properties are listed in Table 5. Note that both Clarkson and Joshi productivity equations are used in our FMB technique for the field example for the purpose of comparison. The comparison can assist in the later crosschecking. The extracted permeabilities using both equations are listed in Table 6.

Figure 9. The single-phase (water) FMB of the field case: (a) the diagnostic plot of single-phase (water) and (b) the straight line.

Table 6. Extracted properties of the field example.

Calculated Value	Single-Phase (Water) FMB	Two phase (Water + Gas) RTA	
	Boundary-Dominated Flow	Early Radial Flow	Linear Flow
Extracted properties	OWIP = 157,516 stb, $A_{dra} = 211.34$ acres, $y_d = 156$ m, $k_{yJ} = 2.892$ mD, $k_{yC} = 2.406$ mD	$k_y k_{zs} = 0.159$ $k_z = 0.061$ mD *	$k_y = 2.572$ mD

* k_z is calculated using average value of k_{yJ} , k_{yC} and k_y .

After the FMB study in our workflow, the analysis of two phase RTA starts with the correction of the RNP using the appropriate water saturation. To identify the flow regimes, average water saturation calculated using the whole drainage area (obtained by the single-phase FMB) is utilized to identify the early radial flow and formation linear flow regimes on the diagnostic plot (Figure 10a). Note that we cannot use the water saturation in the AI for the diagnostic plots because the flow regimes are not yet identified. Hence, the slopes of each flow regime are not exactly equal to the standard values, which are unit slope for boundary-dominated flow, half slope for formation linear flow, and zero slope for early radial flow. Nonetheless, the slope of each flow regime can still be identified due to its sequence and unique characteristics.

Figure 10. The use of two phase RTA techniques for analyzing flow regimes associated with a horizontal well in the field example: (a) diagnostic curve (RNP*), (b) diagnostic curve (derivative), (c) early radial flow of gas phase, and (d) formation linear flow.

After the flow regimes are identified in Figure 10a, average water saturation values in the AI can be precisely calculated in both early radial flow and transient formation linear flow regimes. Finally, reservoir properties can be later estimated using the presented methods to correct RNP and extract reservoir properties.

Figure 10a,b shows the diagnostic plot and its derivative for two phase RTA for the field example. Due to the long horizontal interval (8960 ft) and short production time (2.5 year), only early radial flow and transient formation linear flow regimes are identified. For early radial flow and transient linear flow regimes of the field example, the water saturation in the AI is obtained using Equations (5) and (9), respectively. Due to the fluctuation of the gas production rate, the superposition time ($t_{ca,isp}$) is employed for the field case. The geometric-average permeability is obtained using the water saturation in the AI in the early radial flow regime (Figure 10c).

Because the boundary effects have not yet dominated the flow, only the horizontal permeability of coal (k_y) can be extracted using the straight-line slope when $k_{rg} \times RNP_g$ is plotted versus superposition time ($t_{ca,isp}$) in the transient linear flow regime (Figure 10d). In each flow regime, the slopes of the straight lines are employed to extract the reservoir permeabilities and the OGIP using our proposed two phase RTA technique. The results obtained from the slopes from Figure 10b–d can be seen in Table 6.

In Table 6, reservoir information obtained using both the proposed single-phase (water) FMB and two phase (water + gas) RTA methods can be crosschecked. The proposed single-phase FMB method is applied to extract the OWIP, the drainage area of the horizontal well, the investigation distance (based on the rectangle shape of the drainage area), and horizontal permeability. Because the relative position of the horizontal well in the drainage area is close to that of model 2, the permeability values obtained using the Joshi and Clarkson equations are similar in Table 6, and are also similar to the results from the two phase RTA study. This crosscheck ensures the consistency between the FMB and the two phase RTA. For the two phase RTA study, because the boundary-dominated flow regime is not observed, k_y and k_z are calculated in the early radial flow and transient linear flow regimes. The vertical permeability of coal (k_z) is extracted to be 0.061 mD when $k_y = 2.623$ mD (calculated using the average value of k_{yJ} , k_{yC} , and k_y).

The extracted k_y is the average permeability of the coal seam along the horizontal interval (8960 ft). The coal permeability extracted by the proposed single-phase (water) FMB and two phase RTA are in good agreement with the coal permeability measured by the core analysis. The integrated analysis of early radial and formation linear flow regimes provides a realistic estimation of coal permeability along the horizontal interval.

5. Conclusions

In this study, a workflow is presented including the single-phase (water) FMB method and two phase RTA, using the concept of the AI, to analyze gas and water production data in horizontal CSG wells and extract reservoir properties. Simulation cases and a field case are presented to validate the proposed workflow and the application of the improved techniques. The conclusions can be drawn as follows:

- (1) The permeability extracted from the single-phase FMB method requires an appropriate productivity equation. The flow regime prior to boundary-dominated flow determines the type of production equation. The Joshi equation is suitable for the situation in which elliptical flow obviously occurs before boundary-dominated flow, and the Clarkson equation works well for the situation in which formation linear flow exists prior to boundary-dominated flow.
- (2) The average water saturation of the drainage area is obtained using the OWIP from single-phase (water) FMB. The accuracy of this water saturation is sufficient to identify the flow regimes from a diagnostic plot in the two phase RTA technique. However, the water saturation in the AI is necessary for the extraction of properties in each flow regime.

- (3) A workflow application to a field example from the Qinshui Basin indicates that the proposed single-phase (water) FMB and two phase RTA methods can be utilized simultaneously to improve the accuracy of properties' extraction from the production history. The proposed workflow in this study can extract the reservoir permeabilities and OGIP with acceptable accuracy.

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Nomenclature

Abbreviations

AI	area of influence
CSG	coal seam gas
DDA	Dynamic drainage area
FMB	flowing material balance
OGIP	original gas-in-place
OWIP	original water-in-place
PDA	production data analysis
RNP	rate-normalized pressure
RNP*	rate-normalized pressure modified using water saturation
RTA	rate-transient analysis

Field variables

a	half the major axis of the drainage ellipse, ft
A_{dra}	area of drainage in CSG reservoir, acre
b	y-axis intercept of the straight-line on specialty plot
b_{pps}	inverse of productivity index for water, Scf/Psi
B_g	gas formation volume factor, reservoir volume to surface volume
B_w	water formation volume factor, reservoir volume to surface volume
c_d	desorption compressibility, Psi^{-1}
c_f	formation rock compressibility, Psi^{-1}
c_g	gas compressibility, Psi^{-1}
c_t	total compressibility of coal seam gas reservoir, Psi^{-1}
c_t^*	total compressibility including desorption effects, Psi^{-1}
c_w	water compressibility, Psi^{-1}
f_{cp}^*	correlation factor in linear flow, dimensionless
G_i	original gas-in-place, MMscf
G_p	cumulative gas production, MMscf
h	formation thickness, ft
k_{rg}	relative permeability of gas, fraction
$\bar{k}_{rg}$	average relative permeability of gas in corresponding flow regime, fraction
k_{rw}	relative permeability of water, fraction
k_y	horizontal permeability of coal seam, mD
k_{yJ}	horizontal permeability extracted using Joshi equation, mD

k_{yC}	horizontal permeability extracted using Clarkson equation, mD
k_z	vertical permeability of coal seam, mD
L_w	the length of horizontal well, ft
L_x	the length of drainage area on x axis, ft
m	slope of the straight-line on specialty plot
$m(p)$	real gas pseudo pressure, Psi^2/cp
$m^*(p)$	corrected real gas pseudo pressure, Psi^2/cp
N_w	the water volume-in-place, Stb
p	pore pressure in coal seam, Psi
$\bar{p}_{AI}$	average pressure in area of influence, Psi
p_i	initial pressure of reservoir, Psi
p_L	Langmuir pressure of reservoir, Psi
p_0	the reference pressure, Psi
p_R	average pressure of the reservoir, Psi
p_{sc}	pressure at standard condition, Psi
p_{wf}	flowing bottom-hole pressure, Psi
Δp	production pressure drop in coal seam, Psi
q_g	gas production flow rate, Scf/d
q_w	water production flow rate, Stb/d
r_e	equivalent drainage area radius, ft
r_w	wellbore radius, ft
s_g	gas saturation, fraction
s_w	water saturation, fraction
t	production time, day
T	temperature, F
t_a	the material balance time of water production, day
t_{ca}	the material balance pseudo time accounting for desorption effect, day
$t_{ca,isp}$	the superposition time of linear flow regime, fraction
$t_{ca,rsp}$	the superposition time of radial flow regime, fraction
T_{sc}	temperature at standard condition, F
V_{coal}	gas content of coal, Scf/ft ³
V_L	Langmuir volume, Scf/ton
W_p	cumulative water production, Stb
W_e	water influx of external source, Stb
y_{AI}	the distance of formation linear flow regime, ft
y_d	the distance of drainage area, ft
z	gas deviation factor, fraction
Z_{sc}	gas deviation factor at standard condition, fraction
Z^*	gas deviation factor for material balance method of CSG reservoir, fraction
Z^*_i	initial gas deviation factor for material balance method of CSG reservoir, fraction
<i>Greek variables</i>	
β	ratio of coal horizontal permeability and vertical permeability, dimensionless
δ	the coefficient for production constraint, dimensionless
ρ_c	density of coal rock, g/cm ³
μ_w	gas viscosity, mPa·s
μ_g	gas viscosity, mPa·s
$\bar{\mu}_g$	average gas viscosity, mPa·s
μ_{gi}	initial gas viscosity, mPa·s
φ	coal cleat porosity, fraction
$\bar{\varphi}$	average coal cleat porosity, fraction
φ_i	initial coal cleat porosity, fraction

Appendix A. Single-Phase (Water) FMB Equations for a Horizontal Well

During the early production period (single-phase water flow), when the water rate is constant, the RNP_w (rate-normalized pressure for water production) can be expressed by:

$$RNP_w = \frac{p_i - p_{wf}}{q_w} \quad (A1)$$

When the boundary-dominated flow regime is observed, coal permeability and OWIP can be derived using the FMB technique developed for a horizontal well. A unit slope straight line on the diagnostic plot (the plot of RNP_w versus t_a) indicates that boundary effects have dominated the water flow. t_a is the material balance time for water production and is expressed by:

$$t_a = \frac{N_w}{W_p B_w} \quad (A2)$$

The derivation of the FMB for a horizontal well begins with the water compressibility equation, where the difference between initial reservoir pressure and average reservoir pressure can be calculated by Equation (A3):

$$p_i - p_R = \frac{W_p B_w}{N_w c_t} \quad (A3)$$

Having the water productivity equation, the difference between average reservoir pressure and bottom-hole pressure can be calculated by Equation (A4):

$$p_R - p_{wf} = q_w \times b_{pss}, \quad q_w = \frac{p_R - p_{wf}}{b_{pss}} \quad (A4)$$

Adding Equation (A3) to Equation (A4) and rearranging the result in the general form of the FMB equation for water yields:

$$\frac{q_w}{\Delta p} = -\frac{W_p B_w}{\Delta p c_t} \frac{1}{N_w b_{pss}} + \frac{1}{b_{pss}} \quad (A5)$$

In Equation (A5), b_{pss} accounts for the pressure loss due to the pseudo-steady state inflow of fluid (Equation (A4)). Equation (A5) can be linearized to extract coal permeability and OWIP when the productivity equation is known and results in:

$$\left\{ \begin{array}{l} \frac{q_w}{\Delta p} = -mx + \frac{1}{b_{pss}} \\ x = \frac{W_p B_w}{\Delta p c_t}, \quad m = -\frac{1}{N_w b_{pss}} \end{array} \right. \quad (A6)$$

Equation (A6) indicates that there is a linear relationship between the pressure-normalized rate and the normalized cumulative production in the boundary-dominated flow regime. The slope and intercept of the straight line can be utilized to calculate the OWIP (N_w). When porosity and thickness are known, the drainage area of the horizontal well can be calculated. The average permeability of the coal seam can be extracted using the intercept ($1/b_{pss}$), which requires the choice of an appropriate productivity equation.

Because the rate of pressure decline at the flow boundary is small for a horizontal well, the productivity equations of steady state flow may be selected to extract the permeability. Depending on the relative position of the horizontal well in the drainage area, elliptical or formation linear flow regimes may occur, followed by the boundary-dominated flow regime.

The productivity of a horizontal well can be described using the Joshi equation [46] for an elliptical drainage area, or the Clarkson equation [28] for formation linear flow, which are shown as below:

$$q_w = \frac{k_y h (p_R - p_{wf}) / (\mu_w B_w)}{141.2 \left[\ln \frac{a + \sqrt{a^2 - (L_w/2)^2}}{L_w/2} + \beta^2 \frac{h}{L_w} \ln \frac{h}{2r_w} \right]} \quad (\text{A7})$$

$$q_w = \frac{k_h h (p_R - p_{wf}) / (\mu_w B_w)}{141.2 \left(\frac{4y_d}{\pi L_w} \right)} \quad (\text{A8})$$

where (a) is the half major axis of the drainage ellipse and the drainage distance (y_d) can be estimated using the following equations:

$$\begin{cases} y_d = \frac{OWIP}{\phi h L_w}, r_e = \sqrt{\frac{OWIP}{\phi h \pi}} \\ a = (L_w/2) \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{(L_w/2r_e)^4}} \right]^{0.5} \end{cases} \quad (\text{A9})$$

Generally, horizontal permeability of the coal seam is greater than the vertical permeability, and the horizontal drainage area is also much larger than the vertical drainage area. Hence, the contribution of vertical flow is negligible in the boundary-dominated flow regime in under-saturated CSG reservoirs, and b_{pss} using both productivity equations can be written as:

$$b_{pss} = \frac{141.2(\mu_w B_w) \left[\ln \frac{a + \sqrt{a^2 - (L_w/2)^2}}{L_w/2} \right]}{k_y h} \quad (\text{A10})$$

$$b_{pss} = \frac{141.2(\mu_w B_w) \left(\frac{2\pi y_d}{L_w} \right)}{k_y h} \quad (\text{A11})$$

Finally, the horizontal permeability of the coal can be extracted using Equations (A10) and/or (A11).

Table A1. Conversion Table.

Quantity	Field Unit	SI Unit
Pressure	1 psi	6894.76 Pa
Length	1 ft.	0.3048 m
Volume	1 stb	0.159 m ³
	1 sft ³ or 1 Scf	0.0283 m ³

Appendix B. Two Phase RTA Equations of CSG Reservoirs

In under-saturated CSG reservoirs, pseudo-pressure, $m^*(p)$, and material balance pseudo-time (t_{ca}) are used to account for relative permeability, gas-property variation, and desorption effect with pore pressure [9,12]. $m^*(p)$ and t_{ca} can be obtained using Equations (A12) and (A13), respectively.

$$m^*(p) = 2 \int_{p_0}^p \frac{k_{rg} p}{\mu_g z} dp \quad (\text{A12})$$

$$t_{ca} = \frac{(c_t^* \mu_g)_i}{q_g} \int_0^t \frac{q_g}{c_t^* \mu_g} dt \quad (\text{A13})$$

This integral process needs to seek the relationship between average water saturation and average reservoir pressure [5]. The total compressibility (c_t^*) in t_{ca} includes the effect of desorption on gas compressibility, shown by Equation (A14). The desorption compressibility (c_d) is calculated using Equation (A15).

$$c_t^* = s_w c_w + c_f + c_d + s_g c_g \quad (A14)$$

$$c_d = \frac{B_g \rho_c V_L p_L}{32.04(p_R + p_L)^2 \varphi} \quad (A15)$$

For two phase RTA, the RNP* can be used for a diagnostic plot to identify flow regimes. Once the flow regimes are identified, straight-line methods are used to extract reservoir properties. In the application of the straight-line technique, single-phase RNP is modified using the gas relative permeability values. Two forms of RNP for two phase RTA in under-saturated CSG reservoirs can be expressed by the following equations:

$$RNP_g^* = \frac{m^*(p_i) - m^*(p_{wf})}{q_g} \quad (A16)$$

$$\bar{k}_{rg} \times RNP_g = \frac{\bar{k}_{rg} [m(p_i) - m(p_{wf})]}{q_g} \quad (A17)$$

For a horizontal well that penetrates most part of the drainage area, the pressure decline in the transient formation linear flow regime can dramatically influence the fluid properties. Hence, the correction factor (f_{cp}^*) must account for the change in gas properties [14,45], which can be written as:

$$f_{cp}^* = \sqrt{\frac{(\mu_g c_t^*)_i}{\mu_g c_t^*}} \quad (A18)$$

Commonly, in transient flow regimes, neither the production rate nor the bottom-hole pressure can be maintained at constant levels. The flow regime can be identified using material balance pseudo-time (t_{ca}), but property extraction using straight-line techniques requires the superposition time. The superposition time for early radial flow and transient linear flow regimes can be expressed as:

$$t_{ca, rsp} = \sum_{i=1}^n \frac{(q_{gi} - q_{gi-1})}{q_{gn}} \log[(t_{ca})_i - (t_{ca})_{i-1}] \quad (A19)$$

$$t_{ca, lsp} = \sum_{i=1}^n \frac{(q_{gi} - q_{gi-1})}{q_{gn}} \sqrt{(t_{ca})_i - (t_{ca})_{i-1}} \quad (A20)$$

For the boundary-dominated flow regime, the average pressure and water saturation are needed when the two phase flowing material balance method is applied. Seidle's MBE [10] is widely used to calculate both average reservoir pressure and average water saturation [5,29], expressed using Equations (A21)–(A23). An iterative calculation process is needed to obtain average pressure and average water saturation during boundary-dominated flow.

$$\frac{p}{Z^*} = \frac{p_i}{Z_i^*} \left(1 - \frac{G_p}{G_i}\right) \quad (A21)$$

$$Z^* = \frac{z}{\frac{\rho_c V_L p_{sc}}{32.037 \varphi_i Z_{sc} T_{sc} (p + p_L)} + (1 - s_w) \exp[-c_f(p_i - p)]} \quad (A22)$$

$$s_w = \frac{s_{wi}[1 + c_w(p_i - p)] + \frac{B_w(W_e - W_p)}{7758.4A_{dra}h\phi_i}}{\exp[c_f(p_i - p)]} \quad (A23)$$

For the two phase (water + gas) RTA, the straight-line techniques and parameter extraction equations derived for tight and shale gas reservoirs can still be used to calculate the reservoir and stimulation parameters in under-saturated CSG reservoirs. An early radial flow regime that exists for a short production period may not be captured by early production data. If early radial flow can be identified, the geometric-average permeability $\sqrt{k_y k_z}$ can be extracted. k_y is the coal permeability perpendicular to the horizontal interval and k_z is the vertical permeability of the coal seam. The horizontal permeability (k_y) can be extracted from the transient linear flow and the OGIP can be estimated by the end time of the formation linear flow regime using the end time of linear flow (t_{ehs}) and the equation listed in Table 1.

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