

Research Article

An Efficient and Robust Method to Predict Multifractured Horizontal Well Production in Shale Oil and Gas Reservoirs

Ling Chen , Yuhu Bai, Bingxiang Xu, Yanzun Li, Zhiqiang Dong, and Suran Wang 

CNOOC Research Institute Co., Ltd., Beijing 100028, China

Correspondence should be addressed to Ling Chen; chenling10@cnooc.com.cn

Received 28 May 2021; Revised 20 July 2021; Accepted 30 July 2021; Published 12 August 2021

Academic Editor: Tianshou Ma

Copyright © 2021 Ling Chen et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Shale oil and gas reservoirs are developed by MFHWs. After large-scale hydraulic fracturing, it is hard to forecast the production rate using the theoretical method. In the engineering application field, the empirical method of DCA is often used to forecast the production rate of shale oil and gas produced by MFHWs. However, there are some problems in using DCA, like how to find out the proper decline model and switch point of two contiguous flowing periods and how to deal with the unsteady operation condition which causes a lot of uncertainty in production forecast. In order to solve these problems, firstly, a straight line model, representing the linear flow period in the life cycle of shale oil and gas produced by MFHWs, in the $(Q, \lg q)$ coordinate system is proven to be theoretically proper. Secondly, the duration of the linear flow period is verified to be over 10~15 years by using an analytical model to do the calculation with the method of Monte Carlo random sampling taking a large amount of parameter combinations of Eagle Ford shale oil and gas reservoirs into calculation. And a field data analysis of Barnett and Eagle Ford also shows that the duration of linear flow period can be more than 10~15 years. Thus, a method of production forecast taking advantage of the straight line feature in the $(Q, \lg q)$ coordinate system is raised. After practical use, it is found that the method is robust and can increase the forecast efficiency and decrease the manual error. Moreover, it can increase the accuracy of production forecast and deal with some unsteady operation conditions. Therefore, this new method has good promotional value in the engineering field.

1. Introduction

Shale oil and gas reservoirs are developed by MFHWs (short for multifractured horizontal wells). After large-scale hydraulic fracturing, a complex fracture network forms in the reservoir, which makes it difficult to describe the formation of network and study fluid flow law in the reservoir. Therefore, it is hard to forecast the production rate of MFHWs in shale oil and gas reservoirs using the theoretical method. In the field of engineering application, in most cases, an empirical method of DCA (short for decline curve analysis) is used to forecast the production rate of shale oil and gas, because of its advantages in overall forecasting efficiency and accuracy.

However, there are still some problems in using DCA when forecasting the production rate of MFHWs. As in the process of shale oil and gas produced by MFHWs, there are

several flowing periods and each flowing period has different flowing characteristics, which cause it to be difficult to conduct DCA using a single model with the purpose of achieving high accuracy. So the common solution is to use a multistage combined decline model to increase the adaption of the multiple flowing periods. The first problem is choosing a proper decline model for each flowing period in which strong subjectivity often exists. The second problem is deciding the switch point of two contiguous flowing periods which even has no theoretical basis. Obviously, these two problems will bring big uncertainty in the forecast results and constrain the increasing of forecasting accuracy. The third one is that usually a DCA is conducted under the condition of steady flowing pressure. When the operation condition changes, there is no way to deal with it. In order to solve these problems, it is necessary to carry out theoretical research and find the theoretical base of how to find out the proper decline

model, how to deal with the uncertain switch point, and how to handle the unsteady operation condition which is often met.

In this paper, a straight line forecast method with a theoretical basis which can be broadly used in shale oil and gas reservoirs produced by MFHWs is newly raised. By using this method, the efficiency and accuracy of production forecast can be increased and at the same time the applicability of unsteady operation condition can be increased.

The research result of MFHW production performance in shale oil and gas reservoirs shows that there are mainly three flowing periods: early-stage transient flow period, linear flow period, and boundary-dominated flow period [1–4]. The linear flow period can be subdivided into transient linear flow period and compound linear flow period, and it is the most important flowing period of shale oil and gas production cycle produced by MFHW [5–9]. After formula manipulation of the linear flow model [10–14], it shows that the cumulative production Q has a linear relation to the logarithm of production rate q . This characterization on the one hand tells that, in the linear flow period, the production decline law matches Arps' decline law with decline index $n = 1$; on the other hand, it can take the advantages of the straight line in $(Q, \lg q)$ coordinate system to increase the efficiency and accuracy of the production forecast. An analytical model is used to calculate the time duration of the linear flow period. In this process, the reservoir parameters and fluid PVT parameters are gained from Eagle Ford shale oil and gas reservoirs, and the Monte Carlo random sampling method is used to determine a large amount of parameter combinations. Calculation results showed that the time duration of the linear flow period is often over 10~15 years. A field data analysis is also used to study the time duration of the linear flow period. After analyzing the production date of Barnett shale gas reservoir and Eagle Ford shale oil and gas reservoir, it is found that the duration of linear flow period usually can be more than 10~15 years. During the production of shale oil and gas, the initial production rate is very high and the production also decreases very rapidly. Usually, in the first 3 years, the cumulative production can reach 50% of economic recovery, and in the first 10 years, the cumulative production can reach 80% of economic recovery. When taking economy into consideration, the production time of shale oil and gas wells is less than 20 years, which means the linear flow period occupies the majority of the production cycle. So it is reasonable to conduct the production forecast based on the characterization of linear flow. Field test shows that the newly raised method has better production forecast accuracy than the widely used modified hyperbolic Arps' method [15–17], and the average forecast accuracy can achieve about 90%. In addition, the new method also has the ability to deal with some unsteady operation conditions when flowing pressure rose up or the well resumed producing after a temporary shutting down.

Above all, using the straight line feature in $(Q, \lg q)$ coordinate system to do the production forecast of shale oil and gas developed by multifracted horizontal well is proved to be a robust method and can increase the forecast efficiency a lot. It has good promotional value in the engineering field.

2. Flowing Period of Shale Oil and Gas Reservoirs Produced by Multifracted Horizontal Well

Shale oil and gas reservoirs are developed by multifracted horizontal wells. During the production process, firstly, the reservoir fluid will flow into the stimulated region via the tight shale matrix, and then flow into the major fractures, and lastly flow into the wellbore through fracture. Because of the big differences in pore structure and permeability of these flow media, many researchers consider that there are several flowing periods in the shale oil and gas reservoirs developed by MFHWs. The main three flowing periods are early-stage transient flow period, linear flow period, and boundary-dominated flow period [1–4]. The early-stage transient flow period is affected by wellbore storage effect, major fracture distribution, and inflow fluid characteristics when fracturing, and its duration is very short, which causes it to be hard to analyze. Midterm linear flow period is mainly affected by the characteristics of reserve and fluid and the parameters of fracturing transformation, and its duration is relatively long. The production data of this period is used to do a lot of studies to analyze the fracture parameters of MFHWs and the permeability of stimulated volume. The last boundary domain flow period is determined by the well spacing of well pattern, the area of well controlled, and matrix permeability, and the production data of which period is mainly used to analyze the decline law in the end of the production life cycle.

As linear flow is the most important flowing period, there are a lot of research achievements of its flowing theory and modeling. And as the research further develops, the linear flow period can be subdivided into transient linear flow period [5, 6] and compound linear flow period [7, 8]. The transient linear flow period indicates the flow that occurs in the stimulated volume, in which the reservoir fluid flows perpendicularly to the fracture. The compound linear flow adds the flowing period that the reservoir fluid in the weak stimulated volume flows perpendicularly to the strong stimulated volume. These phenomena match the traditional theory of trilinear flow of MFHWs [9], and correspondingly, the enhanced frac region (EFR) model and multfrac composite (MFC) model are built to characterize the compound linear flow [10, 11]. No matter the transient linear flow or the compound linear flow, they are both linear flows and share the same flowing model. The research of linear flow shows that in the condition of constant flowing pressure which has the same condition of DCA the reciprocal of production has a linear ordered relation with square root time [12–14] as

$$\frac{1}{q} = m\sqrt{t} + b. \quad (1)$$

The production q integration in Equation (1) gains the cumulative production Q as

$$Q = \int_0^t q dt = \int_0^t \frac{1}{m\sqrt{t} + b} dt. \quad (2)$$

Set $x = \sqrt{t}$, and the limit of integration changes to $(0, \sqrt{t})$, so Equation (3) is obtained.

$$Q = \int_0^{\sqrt{t}} \frac{2x}{mx+b} dx. \quad (3)$$

Finally, the definite integration result of Equation (3) is

$$Q = \frac{2}{m} \left[\sqrt{t} - \frac{b}{m} \ln(m\sqrt{t} + b) + \frac{b}{m} \ln b \right]. \quad (4)$$

Bring Equation (1) into Equation (4); Equation (5) is obtained.

$$Q = \frac{2}{m^2} \left(\frac{1}{q} - b \ln q - b + b \ln b \right). \quad (5)$$

Usually, in the linear flow period, $q \gg 1$, so $1/q \approx 0$; then, the simplified form of Equation (5) is obtained.

$$Q = \frac{2b}{m^2} (-\ln q - 1 + \ln b). \quad (6)$$

Equation (6) shows a linear order relation of cumulative production Q and logarithm of production rate q .

3. Decline Law of Shale Oil and Gas in Linear Flow Period

Although the flowing law is complex for MFHWs when developing shale oil and gas reservoirs, by statistical law, the production decline feature matches several decline curve models. The first one is the hyperbolic decline model or modified hyperbolic decline model based on Arps' decline theory [18, 19]; the second one is the Duong model which takes the long-term linear flow into consideration [20], and the third one is the stretched exponential decline model established by the principle of statistics and focus boundary dominant flow [21]; and the others are mostly the transformation of combination of the former three models. These three basic models, on the basis of the modeling hypothesis, have different range of application individually (Table 1). However, in regard to the problems of how to choose a suitable multisegment model and how to decide the segment point, there are a lot of empirical methods raised by many researchers [22, 23]. However, no method has a strong theoretical basis, and the difference between the production forecast results calculated by different methods may be large or small.

As a matter of experience in field application, the modified hyperbolic decline model based on Arps' decline theory is the most widely used. The basic formation of Arps' decline model is

$$q = \frac{q_0}{(1 + nD_0t)^{1/n}}. \quad (7)$$

Set $b = 1$, and the production q integration in Equation (7) gains the cumulative production Q as

$$Q = \int_0^t \frac{q_0}{1 + D_0t} dt = \frac{q_0}{D_0} \ln(1 + D_0t). \quad (8)$$

Bring Equation (7) into Equation (8) to eliminate the time t ; Equation (9) showing the relation of cumulative production Q and production rate q is obtained.

$$Q = \frac{q_0}{D_0} \ln q_0 - \frac{q_0}{D_0} \ln q. \quad (9)$$

When comparing Equation (9) with Equation (6), the same format is found, which is the linear order relation of cumulative production Q and the logarithm of production rate q . It is recognized that, in the process of shale oil and gas reservoirs developed by MFHWs, the decline law of the linear flow period matches Arps' decline law with decline index $n = 1$.

4. Validation of the Duration Time of Linear Flow

4.1. Analytical Model Validation. The time of duration of the linear flow period can be calculated by the investigation distance equation [12], which is Equation (10). And the duration time equation is the transformation of Equation (10), which is Equation (11).

$$y = 0.113 \sqrt{\frac{kt}{(\phi\mu c_t)_i}}. \quad (10)$$

$$t = \frac{y^2(\phi\mu c_t)_i}{0.113^2 k}. \quad (11)$$

For the compound linear flow, as it shows in Figure 1, there are two different flow regions with different permeability. The total duration time needs to be calculated separately and then added together.

When the fluid flows through the region with the permeability of k_1 , the corresponding duration time t_1 is calculated by

$$t_1 = \frac{y_1^2(\phi\mu c_t)_i}{0.113^2 k_1}. \quad (12)$$

From Equation (10), the speed of pressure propagation can be obtained as it shows in

$$v(t) = \frac{dy(t)}{dt} = 0.113 \sqrt{\frac{k}{(\phi\mu c_t)_i}} \frac{1}{2\sqrt{t}}. \quad (13)$$

When the fluid flows through the region with the permeability of k_2 , the corresponding relation of flowing distance and duration time is calculated by

TABLE 1: The comparison of the primary decline model.

Name	Equation	States range of application
Hyperbolic decline model	$q(t) = q_i/(1 + nD_i t)^{1/n}$	Decline index $n > 1$; it is suitable for the production forecast of transient flow period.
Modified hyperbolic decline model	$q(t) = \begin{cases} q_i/(1 + nD_i t)^{1/n}, & t < t^* \\ q(t^*)e^{-D_{lm}(t-t^*)}, & t > t^* \end{cases}$	The front part is suitable for the transient flow, and the latter half is suitable for the boundary-dominated flow. The risk is to determine the segment point.
Duong model	$q(t) = q_1 t^{-m} e^{(a/(1-m))(t^{1-m}-1)}$	It is suitable for the production forecast of linear flow period, and it will overestimate in the boundary-dominated flow period.
Stretched exponential model	$q(t) = q_0 \exp[-(t/\tau)^n]$	It is suitable for the production forecast of boundary-dominated flow period, and it will underestimate the production.

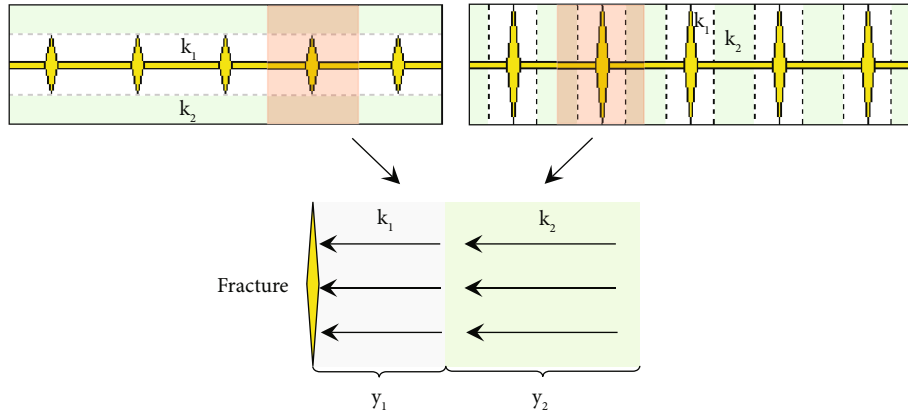


FIGURE 1: Schematic diagram of the compound linear flow model.

$$\begin{aligned}
 y_2 &= \int_{t_1}^{t_2} v(k_2, t) dt = \int_{t_1}^{t_2} 0.113 \sqrt{\frac{k_2}{(\phi\mu c_t)_i}} \frac{1}{2\sqrt{t}} dt \\
 &= 0.113 \sqrt{\frac{k_2}{(\phi\mu c_t)_i}} (\sqrt{t_2} - \sqrt{t_1}).
 \end{aligned} \quad (14)$$

Therefore, the whole time duration of compound linear flow can be calculated by

$$t_2 = \left[\frac{y_1}{0.113} \sqrt{\frac{(\phi\mu c_t)_i}{k_1}} + \frac{y_2}{0.113} \sqrt{\frac{(\phi\mu c_t)_i}{k_2}} \right]^2. \quad (15)$$

As different shale oil and gas reservoirs have different parameters of reserve, fluid, and fracture, it is hard to make a certain decision of the duration time of compound linear flow. Therefore, the theory of probability is brought into use. The basic parameter values and their regularity of distribution are gained from a typical shale oil and gas field, taking Eagle Ford as an example [24–27]. And the Monte Carlo random sampling method is used to determine a large number of parameter combinations, with which the distribution of duration time of compound linear flow can be calculated and an analysis can be done. The typical shale oil and gas reservoirs' parameters for calculating the duration time of compound linear flow is shown in Table 2.

TABLE 2: Parameters for calculation of Eagle Ford.

Parameters (unit)	Value range
Porosity (%)	2~10
Permeability (md)	$1 \times 10^{-5} \sim 1 \times 10^{-3}$
Fracture distance (ft)	150~300
Oil viscosity in reservoir condition	0.5~2
Oil reservoir total compressibility	$8 \times 10^{-6} \sim 1 \times 10^{-5}$
Gas viscosity in reservoir condition	0.02~0.05
Gas reservoir total compressibility	$8 \times 10^{-5} \sim 1 \times 10^{-4}$

After 100,000 times of calculation, the outputs are stable. The result show that no matter the reservoir fluid is oil or gas, the time duration of linear flow is very long, and usually, a duration over 10~15 years can be achieved (Figure 2).

4.2. Production Data Validation. Two sets of production data can also achieve the similar conclusion. Figure 3 shows several production data from Eagle Ford shale with different fluid types. What is shown in Figures 3(a) and 3(b) are typical gas wells that have been in production from 2012 and kept producing for about 8 years. And what is showed in Figures 3(c) and 3(d) are typical oil wells that have been in production from 2013 and kept producing for about 7 years. In the $(Q, \lg q)$ coordinate system, they all show a feature of matching with a straight line and keep no change.

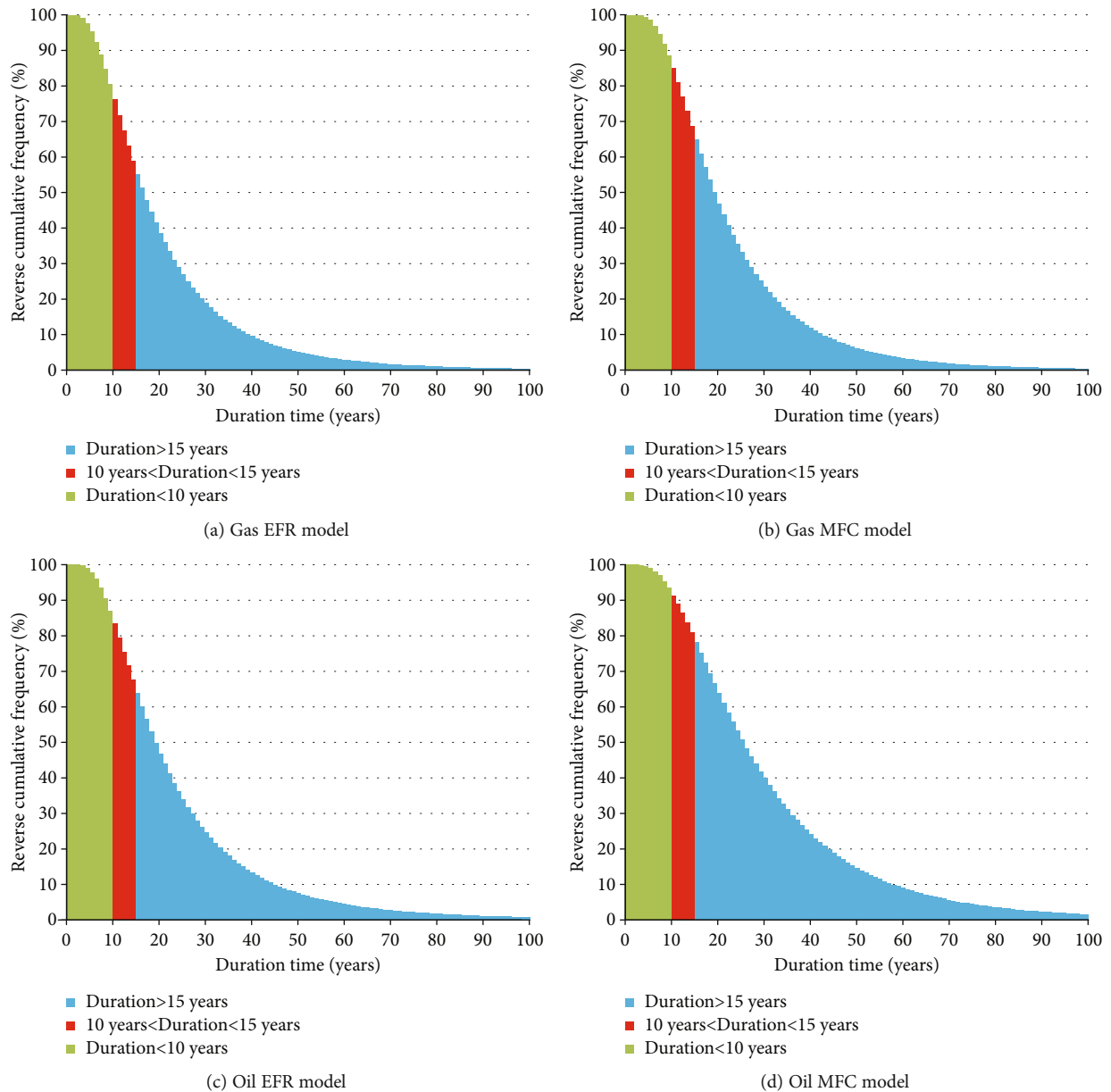


FIGURE 2: Time duration of linear flow of different fluid phases and model.

Figure 4 shows several production data from Barnett shale with different production times. In Figures 4(a) and 4(b), they are two typical wells that have kept producing for about 12 years. In the $(Q, \lg q)$ coordinate system, the feature of straight line appears and keeps no change. In Figures 4(c) and 4(d), they are two typical wells that have kept producing for about 21 years. In the $(Q, \lg q)$ coordinate system, the feature of straight line appears. One well, like Figure 4(c), keeps straight with no change, but another one, like Figure 4(d), appears to show a curve in the end.

According to the above analysis, it is proved that in the linear flow period of shale oil and gas produced by MFHWs, the production decline law matches Arps' decline law with decline index $n = 1$ and the duration time of linear flow can usually last over 10~15 years.

5. Application

During the production of shale oil and gas, the initial production rate is very high and the production also decreases very rapidly. Usually, in the first 3 years, the cumulative production can reach 50% of economic recovery, and in the first 10 years, the cumulative production can reach 80% of economic recovery. When taking economy into consideration, the production time of shale oil and gas wells is less than 20 years, which means the linear flow period occupies the majority of the production cycle. Therefore, the production forecast in 15 years is critically important. According to the research conclusion, it is suggested that when doing the production forecast it is better to use the newly raised $(Q, \lg q)$ coordinate system other than the traditional (t, q) coordinate

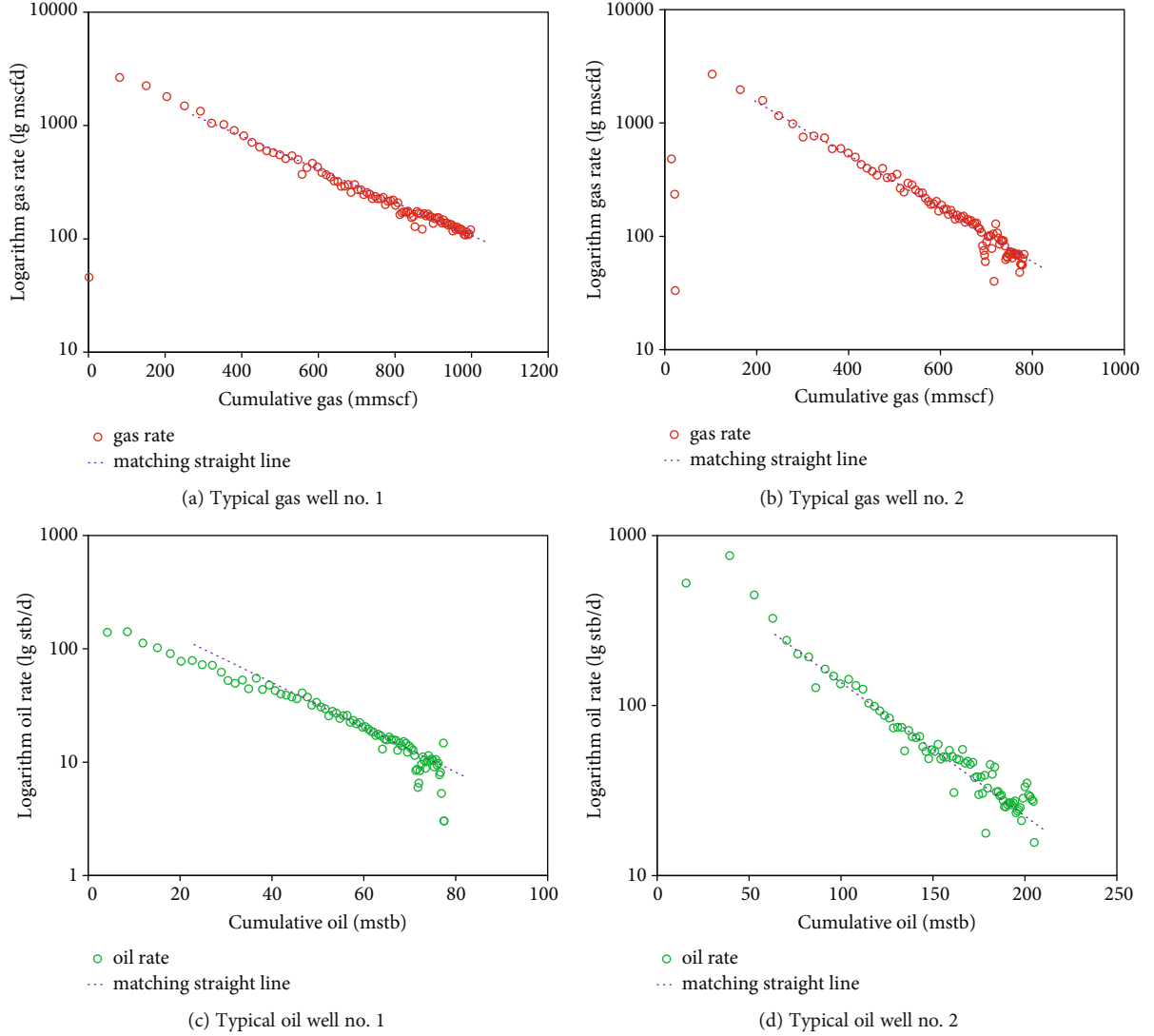


FIGURE 3: Typical production date of Eagle Ford shale.

system, because if we take the advantages of the straight line, on the one hand, it can increase the efficiency of production forecast, and on the other hand, it can decrease the manual error to increase the accuracy of production forecast. In addition, the traditional DCA needs the flowing pressure to be steady, but the new method has the ability to deal with some unsteady flowing pressure cases. The detailed workflow builds upon three steps that are described below.

Step 1. Data regulation: get production rate q and cumulative production Q from shale oil/gas production data. Plot the relationship of q and Q in the $(Q, \lg q)$ coordinate system.

Step 2. Data fitting: fit the straight line feature in the $(Q, \lg q)$ coordinate system and build the linear regression model which should be the form as

$$\lg q = AQ + B. \quad (16)$$

But if there is no straight line feature, we should go back to use the modified hyperbolic decline model to conduct the production forecast.

Step 3. Model transformation: transform Equation (16) to the relationship of q and t , which is usually accepted as the predictive result, shown as

$$q = \frac{1}{10^{-B} - t_c \cdot A \ln 10}. \quad (17)$$

In Equation (17), t_c represents the computing production time and it has a transform relationship with the actual production time t , which is shown in

$$t = t_c - t_{ci} + t_i. \quad (18)$$

5.1. Increasing the Accuracy of Production Forecast. There are actual production data of Barnett shale gas, Eagle Ford shale gas, and Eagle Ford shale oil used to make a comparison of

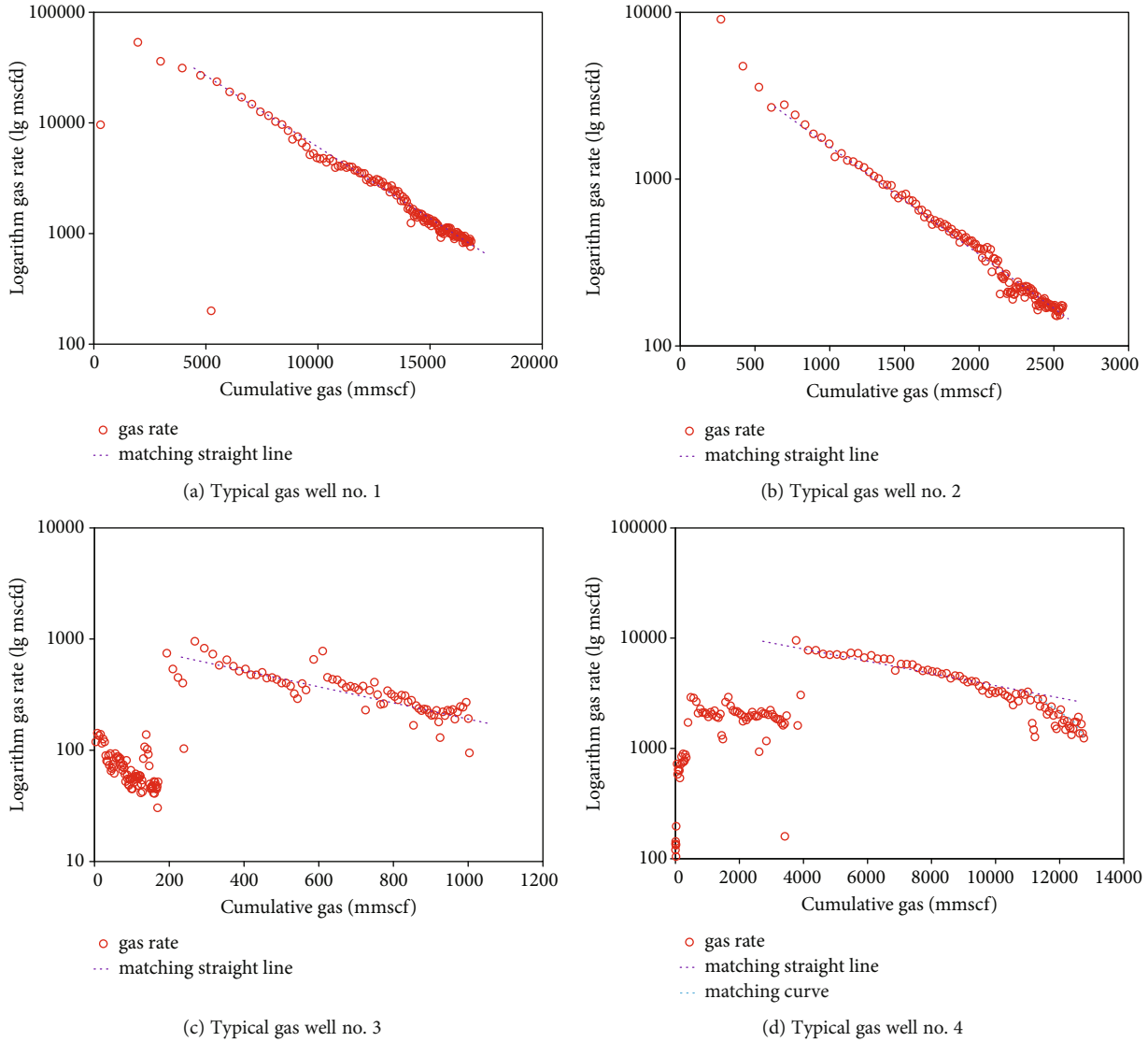


FIGURE 4: Typical production data of Barnett shale.

production forecast accuracy between the newly raised method and the widely used modified hyperbolic decline method. The absolute forecast percentage error (AFPE) is used as the evaluation method of production forecast accuracy, whose computing method is shown in

$$AFPE = \left[1 - \left| \frac{\Delta Q_f}{\Delta Q_a - \Delta Q_f} \right| \right] \times 100\%. \quad (19)$$

Figure 5(a) is the application comparison of the newly raise method and the widely used modified hyperbolic method in Barnett shale gas. The curve fitting of production history is about 2 years, and the extrapolating forecast time is about 10 years. The results of production forecast are that the average accuracy of the newly raised method is 93.9% and the average accuracy of the modified hyperbolic method is 69.8%. Figure 5(b) is the application comparison of the two methods in Eagle Ford shale gas. The curve fitting of produc-

tion history is about 2 years, and the extrapolating forecast time is about 7 years. The results of production forecast are that the average accuracy of the newly raised method is 93.5% and the average accuracy of the modified hyperbolic method is 81.0%. Figure 5(c) is the application comparison of the two methods in Eagle Ford shale oil. The curve fitting of production history is about 2 years, and the extrapolating forecast time is about 5~7 years. The results of production forecast are that the average accuracy of the newly raised method is 89.2% and the average accuracy of the modified hyperbolic method is 79.8%. Overall, the average forecast accuracy of the newly raised method is about 90%, but the average forecast accuracy of the widely used modified hyperbolic method is about 70%~80%. The reasons are that when the newly raised method is used, the decline law is certain and the straight-lined advantage can decrease the manual error.

5.2. *Dealing with the Unsteady Operating Condition.* In traditional DCA, the operation condition of production wells is

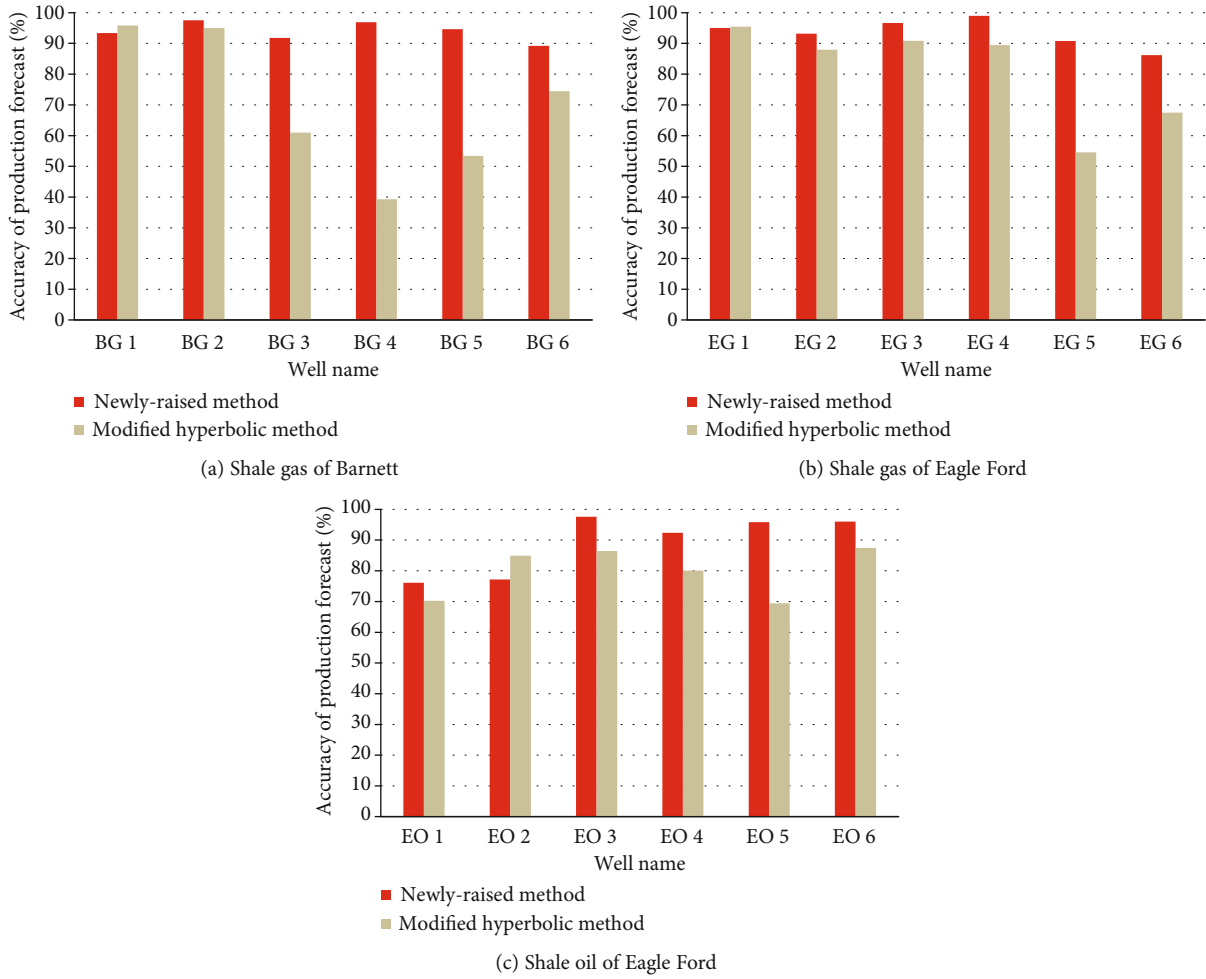


FIGURE 5: Forecast accuracy comparison of two methods.

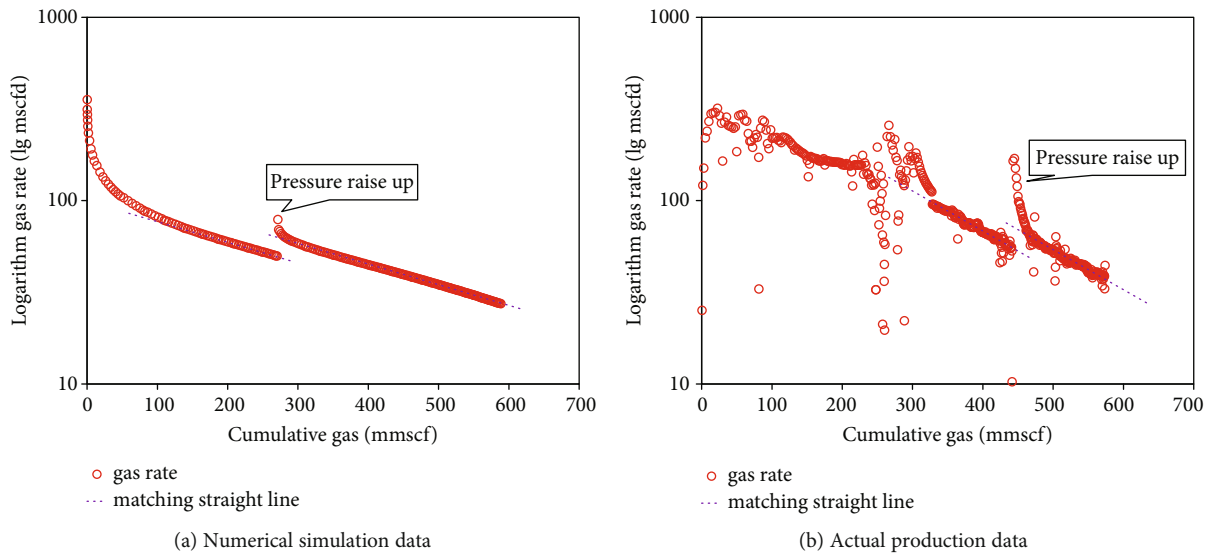


FIGURE 6: Production feature of flowing pressure raising up.

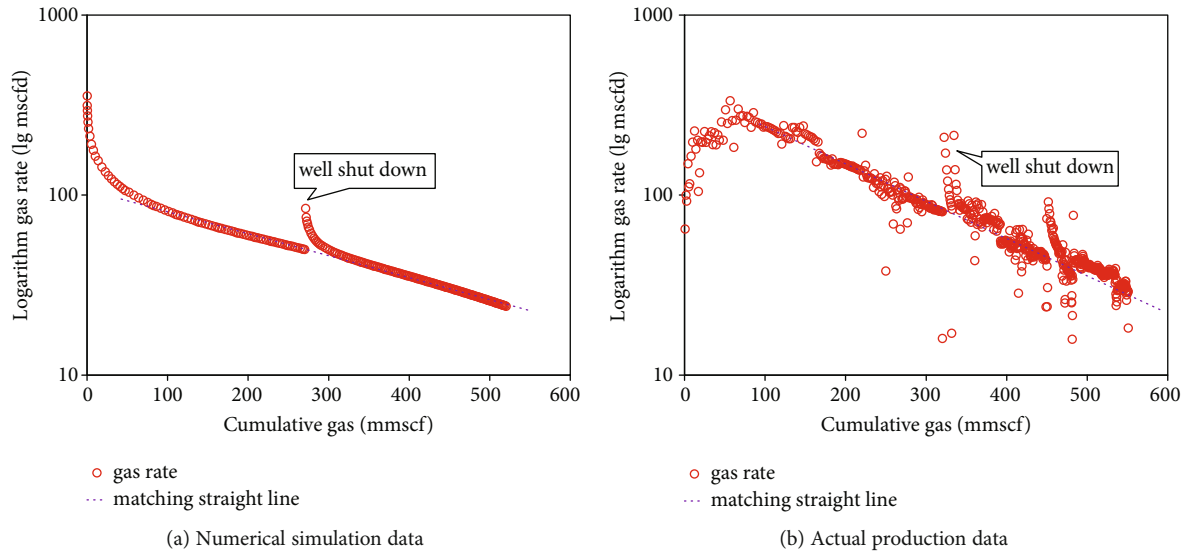


FIGURE 7: Production feature of resuming production after a temporary shutting down.

needed to be stable, which means the flowing pressure usually needs to be steady. However, the reality is stably producing wells are minorities. The unstably producing wells can be classified into two categories: bottom hole pressure dropping down and resuming producing after temporarily shutting down. Based on this research, we suggest that no matter what unsteady operating condition is encountered, keep the production forecast using the last seen straight line feature in the $(Q, \lg q)$ coordinate system, because the changed operation condition cannot change the flowing period. After the changed operation condition comes into being stable again, the flowing feature of the correspondingly flowing period appears again, and the last seen feature is the one we should use in production forecast. What are shown below are the specific methods dealing with each operation condition.

Figure 6(a) shows the numerical simulation of the operation condition that the flowing pressure goes down during the production. The straight line in the $(Q, \lg q)$ coordinate system moves upward parallel. Thus, it is suggested that when doing producing forecast using the newly raised method, the slope of the straight line can be determined by any straight line feature, and the location of the forecast straight line needs to fit for the last seen straight line, as shown in Figure 6(b).

In Figure 7(a), it shows the numerical simulation of the operation condition that the well resumes production after a temporary shutting down. The straight line in the $(Q, \lg q)$ coordinate system keeps extending from the former one after a small disturbance. Thus, it is suggested that when doing producing forecast using the newly raised method, the slope and location of the forecast straight should be determined by the first straight line feature, as shown in Figure 7(b).

6. Conclusions

With the purpose of increasing the production forecast accuracy of shale oil and gas reservoirs developed by MFHWs, this paper completed the theory of DCA and raised a more

efficient DCA method to provide a reference for the engineering field. The main conclusions of this work are as follows:

- (1) During the life cycle of shale oil and gas reservoirs developed by multifracted horizontal wells, the decline law of linear flow period matches Arps' decline law with decline index $n=1$ and shows a straight line feature in $(Q, \lg q)$ coordinate system
- (2) During the life cycle of shale oil and gas production, the duration time of linear flow period lasts long and can usually achieve over 10~15 years, taking up the majority of the life cycle
- (3) A new method of production forecast using a $(Q, \lg q)$ coordinate system and taking advantages of the feature of straight line is raised. The newly raised method can increase the accuracy of the production forecast to about 90%
- (4) The newly raised method can also deal with some unsteady operation conditions like flowing pressure dropping down, resuming production after a temporary shutting down, and flowing pressure rising up. Thereby, it can increase the feasibility of DCA in the engineering field

Nomenclature

- q : Oil or gas production rate (mscfd for gas, bbl/d for oil)
 m : Slope of linear flow analysis ($\text{mscfd}^{-1} \cdot \text{d}^{3/2}$ for gas, $\text{bbl}^{-1} \cdot \text{d}^{3/2}$ for oil)
 t : Production time (d)
 b : Intercept of linear flow analysis (mscfd^{-1} for gas, bbl^{-1} for oil)
 Q : Cumulative production of oil or gas (mscfd for gas, bbl for oil)

q_0 :	Initial oil or gas production rate (mscfd for gas, bbl/d for oil)
D_0 :	Initial decline rate (d^{-1})
n :	Decline index
y :	Distance of investigation (ft)
k :	Permeability (md)
ϕ :	Porosity
μ :	Viscosity (cP)
c_i :	Total compressibility (psi^{-1})
$(\phi\mu c_t)_i$:	The product of porosity, viscosity, and total compressibility ($\text{cp}\cdot\text{psi}^{-1}$) in the initial condition
k_1 :	Permeability of the inner space in compound linear flow (md)
k_2 :	Permeability of the outer space in compound linear flow (md)
y_1 :	Distance of inner space in compound linear flow (ft)
y_2 :	Distance of outer space in compound linear flow (ft)
t_1 :	Time duration of fluid flow through the inner space in compound linear flow (d)
t_2 :	Time duration of the whole compound linear flow period (d)
v :	Speed of pressure propagation (ft/d)
A :	Slope of straight feature in the $(Q, \lg q)$ coordinate system
B :	Intercept of straight feature in the $(Q, \lg q)$ coordinate system
t_c :	Computing production time (d)
t_{ci} :	Computing production time at the beginning of production forecast (d)
t_i :	Actual production time at the beginning of production forecast (d)
ΔQ_a :	Cumulative production of the predictive period for the actual production data (mmscf for gas, stb for oil)
ΔQ_f :	Cumulative production of the predictive period for the forecast production data (mmscf for gas, stb for oil).

Data Availability

The data used to support the findings of this study some are shown within the article, and the others are from LENS database of Wood Mackenzie.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

References

- [1] S. Liu and P. P. Valkó, "Production decline models based on anomalous diffusion stemming from complex fracture network," *SPE Journal*, *SPE-197049-PA*, vol. 24, no. 6, pp. 2609–2634, 2019.
- [2] D. Gunaydin, Z. He, K. G. Brown, M. A. Deasy, M. D. Porter, and D. J. Corinchock, "Long term forecasting in shale reservoirs by using rate transient analysis," in *Paper presented at the SPE Eastern Regional Meeting*, Pittsburgh, Pennsylvania, USA, August 2013.
- [3] M. Nobakht and C. R. Clarkson, "Analysis of production data in shale gas reservoirs: rigorous corrections for fluid and flow properties," *Journal of Natural Gas Science and Engineering*, vol. 8, pp. 85–98, 2012.
- [4] F. Qanbari and C. R. Clarkson, "A new method for production data analysis of tight and shale gas reservoirs during transient linear flow period," *Journal of Natural Gas Science and Engineering*, vol. 14, pp. 55–65, 2013.
- [5] H. Hamdi, H. Behmanesh, and C. R. Clarkson, "A semi-analytical approach for analysis of wells exhibiting multiphase transient linear flow: application to field data," *SPE Journal*, vol. 25, no. 6, pp. 3265–3279, 2020.
- [6] H. Hamdi, H. Behmanesh, and C. R. Clarkson, "A semi-analytical approach for analysis of the transient linear flow regime in tight reservoirs under three-phase flow conditions," *Journal of Natural Gas Science and Engineering*, vol. 54, pp. 283–296, 2018.
- [7] B. Yuan, C. R. Clarkson, Z. Zhang, and X. Zhu, "Deviations from transient linear flow behavior: a systematic investigation of possible controls on abnormal reservoir signatures," *Journal of Petroleum Science and Engineering*, vol. 205, article 108910, 2021.
- [8] Z. Liu and H. Emami-Meybodi, "Rate transient analysis of infinite-acting linear flow by use of piecewise constant diffusivity coefficients," *Journal of Petroleum Science and Engineering*, vol. 196, article 107783, 2021.
- [9] R. S. Jones, "Producing-gas/oil-ratio behavior of multifractured horizontal wells in tight oil reservoirs," *SPE Reservoir Evaluation & Engineering*, vol. 20, no. 3, pp. 589–601, 2017.
- [10] G. E. Slater, J. C. Erdie, and D. L. Raphael, "Simulating the operation of a natural gas distribution system with linear flow models," *Journal of Canadian Petroleum Technology*, vol. 16, no. 4, 1977.
- [11] C. R. Clarkson, F. Qanbari, and J. D. Williams-Kovacs, "Semi-analytical model for matching flowback and early-time production of multi-fractured horizontal tight oil wells," in *Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference*, San Antonio, Texas, USA, August 2016.
- [12] M. Nobakht and C. R. R. Clarkson, "A new analytical method for analyzing production data from shale gas reservoirs exhibiting linear flow: constant pressure production," in *Paper presented at the North American Unconventional Gas Conference and Exhibition*, The Woodlands, Texas, USA, June 2011.
- [13] M. Nobakht and C. R. R. Clarkson, "A new analytical method for analyzing linear flow in tight/shale gas reservoirs: constant-flowing-pressure boundary condition," *SPE Reservoir Evaluation & Engineering*, vol. 15, no. 3, pp. 370–384, 2012.
- [14] C. R. R. Clarkson, M. Nobakht, D. Kaviani, and T. Ertekin, "Production analysis of tight-gas and shale-gas reservoirs using the dynamic-slippage concept," *SPE Journal*, vol. 17, no. 1, pp. 230–242, 2012.
- [15] C. Temizel, C. H. Canbaz, D. P. Onder Saracoglu et al., "Production forecasting in shale reservoirs through conventional DCA and machine/deep learning methods," in *Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference*, Virtual, July 2020.
- [16] B. Li, T. C. Billiter, and T. Tokar, "Rescaling method for improved machine-learning decline curve analysis for unconventional reservoirs," *SPE Journal*, pp. 1–14, 2021.

- [17] B. Li, T. Billiter, and T. Tokar, "Significant error reduction in machine-learning decline curve analysis for unconventional reservoirs," in *Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference*, Virtual, July 2020.
- [18] I. Gupta, C. Rai, C. Sondergeld, and D. Devegowda, "Variable exponential decline: modified Arps to characterize unconventional-shale production performance," *SPE Reservoir Evaluation & Engineering*, vol. 21, pp. 1045–1057, 2018.
- [19] R. D. Hazlett, U. Farooq, and D. K. Babu, "A complement to decline curve analysis," *SPE Journal*, 2021.
- [20] A. N. Duong, "An unconventional rate decline approach for tight and fracture-dominated gas wells," in *Paper presented at the Canadian Unconventional Resources and International Petroleum Conference*, Calgary, Alberta, Canada, October 2010.
- [21] D. Ilk, J. A. Rushing, A. D. Perego, and T. A. Blasingame, "Exponential vs. hyperbolic decline in tight gas sands: understanding the origin and implications for reserve estimates using Arps' decline curves," in *Paper presented at the SPE Annual Technical Conference and Exhibition*, Denver, Colorado, USA, September 2008.
- [22] S. Liu and P. P. Valkó, "A fractional decline model accounting for complete sequence of regimes for production from fractured unconventional reservoirs," *Transport in Porous Media*, vol. 136, no. 2, pp. 369–410, 2021.
- [23] P. Indras and W. J. Lee, "Utility of hybrid forecasting models and diagnostic plots in liquid shales," in *Paper presented at the SPE Hydrocarbon Economics and Evaluation Symposium*, Houston, Texas, May 2014.
- [24] B. Jia, D. Li, J.-S. Tsau, and R. Barati, "Gas permeability evolution during production in the Marcellus and Eagle Ford shales: coupling diffusion/slip-flow, geomechanics, and adsorption/desorption," in *Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference*, Austin, Texas, USA, July 2017.
- [25] A. Sanaei, A. Jamili, J. Callard, and A. Mathur, "Production modeling in the Eagle Ford gas condensate window: integrating new relationships between core permeability, pore size, and confined PVT properties," in *Paper presented at the SPE Western North American and Rocky Mountain Joint Meeting*, Denver, Colorado, April 2014.
- [26] M. Paryani, S. Poludasu, D. Sia, A. Bachir, and A. Ouenes, "Estimation of optimal frac design parameters for asymmetric hydraulic fractures as a result of interacting hydraulic and natural fractures-application to the Eagle Ford," in *Paper presented at the SPE Western Regional Meeting*, Anchorage, Alaska, USA, May 2016.
- [27] F. Siddiqui, A. Rezaei, B. Dindoruk, and M. Y. Soliman, "Eagle Ford fluid type variation and completion optimization: a case for data analytics," in *Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference*, Denver, Colorado, USA, July 2019.