Prediction of critical liquid loading time for water-producing gas wells: Effect of liquid drop rotation

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Abstract

After more than 20 years of continuous development, part of the wells in the Moxilei-1 gas reservoir located at the Sichuan Basin have entered the middle–later production stage. With the continuous decline in formation pressure and production rates, some of the gas wells have entered the potential period of liquid loading, while some have already suffered water plugging. Currently, the field engineers usually carry out some corresponding drainage measures after the occurrence of liquid loading in the gas well, which will first affect the production progress of the gas field, then increase the difficulty in drainage and reduce the drainage effect afterward. On the basis of Pan's model for evaluating critical liquid-carrying flow rate, the influence of liquid drop rotation was considered in the new model. Further, combined with the Arps production decline equation, a prediction model of liquid loading timing was deduced. Taking a typical well in the Moxilei-1 gas reservoir as an example, based on the early-stage production data of the gas well, the model was used to predict the liquid loading timing accurately. The model can predict the possibility and timing of liquid loading in gas wells at different production stages. It can check the gas wells with potential liquid loading, so as to reduce the workload for field workers. Furthermore, it can predict the potential liquid accumulation and its timing in advance, so as to guide the field workers to prepare for drainage in advance.

Keywords Critical liquid-carrying flow model · Liquid drop rotation · Production decline equation · Liquid loading timing · Water-producing well

Introduction

The Moxilei-1 gas reservoir is characterized by low permeability, edge water and sulfur content. In the early stage of development, vertical wells are mainly used. In the middle and late stage of production, it is difficult to bring out the water in the wellbore smoothly due to the rapid decline in production rate. Therefore, it is very easy to accumulate

fluid at the well bottom, increase the back-pressure of the production layer, further reduce the production efficiency of the gas well, then block the wellbore by direct water flooding and damage the formation near the bottom of the well. At present, the corresponding water plugging, water control and drainage measures will be implemented only when the production gas well has effusion symptoms or is completely blocked. On the one hand, the passive implementation of drainage measures will affect the production progress of gas field. On the other hand, it will increase the difficulty in drainage and reduce the drainage effect; in addition, it will increase the workload of field staff and the production cost of single well (Beibei et al. 2013). Therefore, it is very important to accurately predict the liquid loading timing of wellbore for the development and production of oil and gas fields.

At present, direct and indirect methods are mainly used to identify whether the gas well is liquid accumulating or not. The direct methods include visual judgment method, measured pressure gradient curve method, etc. And the indirect methods include critical liquid-carrying model method, condensate

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water calculation method, well test curve analysis method, etc. (Haitao 2017, 2019; Sun et al. 2019a). The critical liquid-carrying model method has a wide range of applications and good application effect (Rui et al. 2019). The critical liquid-carrying model method includes (Rui et al. 2019; Turner et al. 1969; Li et al. 2010, 2001; Jie et al. 2018; Coleman et al. 1991; Min et al. 2001; Chaoyang 2010; Desheng, et al. 2014; Zhibin and Yingchuan 2012; Gang 2014; Sun et al. 2020): (1) the spheroidal droplet model, in which the Turner model is the most classic, but in the actual situation, the circular droplet will be affected by the upper and lower pressure difference in the process of rising in the wellbore, and the droplet will turn to ellipsoidal, so the prediction result of this kind of model is often too large compared with the realistic case (Li et al. 2010; Jie et al. 2018; Coleman et al. 1991), and (2) the ellipsoidal droplet model, in which the Limin model is the most classic (Li et al. 2001; Min et al. 2001), can predict accurately. It is widely used to measure the critical liquid-carrying capacity of gas well, but it ignores the energy loss caused by the tumble of droplets during the rising process (Li et al. 2010). Generally speaking, the critical liquid-carrying model only gives the critical production when the gas well accumulates fluid, and does not propose a targeted prediction method combined with the gas well's own energy. This kind of method cannot predict the specific liquid loading time of gas well in advance and effectively, and its prediction effect is poor for the gas wells with irregular production data and that with violent fluctuation (Sun et al. 2021; Sheikholeslami and Jafaryar 2020; Sheikholeslami and Farshad 2021; Said et al. 2021).

On the basis of Pan's critical liquid-carrying capacity model, the influence of droplet rolling is considered (Li et al. 2010; Jie et al. 2018), and then, combined with Arps production decline equation (Wang et al. 2017, 2020), the prediction model of effusion time in water-producing gas wells is derived. Taking a typical well in Moxilei-1 gas reservoir as an example, based on the production data of the gas well at the early stage, the model is used to predict the time of liquid accumulation and plugging in the gas well accurately. The model can predict the possibility of liquid accumulation in gas wells at different production stages and can reduce the workload of field staff by targeted investigation of gas wells with possible liquid accumulation. In addition, it can predict the gas wells with possible liquid accumulation and the time of liquid accumulation in advance, so as to guide the field staff to prepare for liquid drainage and implement corresponding measures in advance.

Prediction model of liquid loading time in water-producing gas well

Awolusi (2006) and Wei (Na 2007) obtained the following understanding through relevant wellbore fluid-carrying experiments:

1. During the rising process, the droplet will exist as an ellipsoid due to the influence of the pressure difference between the upper and lower parts;
2. During the rising process of ellipsoidal droplets in the wellbore, the pressure difference between the two ends of the droplets is unbalanced, which causes the droplets to roll up and down disorderly, and consumes the gas-carrying energy, which reduces the gas-carrying efficiency.

Therefore, the droplets carried by gas flow in the gas wellbore are ellipsoidal, and the energy loss caused by droplet rolling cannot be ignored.

Ellipsoidal droplet model considering rolling

(1) Advantages and disadvantages of traditional ellipsoidal droplet models

The ellipsoidal droplet model is based on the Turner model, which is the most studied and classic critical liquid-carrying flow model (Rui et al. 2019). Statistics of some spheroid models and ellipsoid models are summarized in Table 1. It can be found that although the ellipsoid model considers many factors, it does not consider the influence of rolling in the process of droplet rising.

Li et al. (2010) and others consider that the gas-carrying flow rate after considering droplet rolling is between the calculation results of Li's ellipsoid model and Coleman's spheroid model, and the energy loss caused by droplet rolling is characterized by adding a correction factor, as follows:

$$v_H = v_L + s(v_T - v_L) \quad (1)$$

In the above formula, V_H , V_L and V_T are the critical liquid loading velocity in He's model, Li's model and Turner model, respectively, fall into the range from 0~1. And s is the correction factor in He's model. The larger the correction factor is, the smaller the energy loss caused by rolling is. According to a large number of field production examples, Li et al. (2010) obtained that the empirical correction factor was equal to 0.83. He's model is based on Li's model and Turner model. These two basic models ignore the influence of droplet deformation, temperature, pressure and other factors and limit the prediction results between the two models. Moreover, He's model contains empirical parameters. Generally speaking, the application scope of the model has great limitations.

(2) An ellipsoidal droplet model considering rolling

According to the research of Jie et al. (2018), the calculation formula of the maximum windward surface diameter after considering the droplet deformation is as follows:

Table 1 Part of classical spheroid model and ellipsoid model

Time	Model	Model features
1969	Turner model (Turner et al. 1969)	The droplet is a round sphere, which is the most classic, but the prediction result is too large. It is suitable for wells with high gas–liquid ratio and foggy flow
1991	Coleman model (Coleman et al. 1991)	According to Turner model, the droplet is a sphere, which is suitable for wellhead pressure less than 3.25mpa
2001	Li model (Li et al. 2001; Min et al. 2001)	According to Turner model, the droplet is ellipsoid
2010	Chaoyang model (Chaoyang 2010)	According to Turner model, the droplet is an ellipsoid with aspect ratio of 0.9
2010	Desheng model (Desheng et al. 2014)	According to Turner model, small droplets aggregate into large droplets
2012	Zhibin and Yingchuan model (Zhibin and Yingchuan 2012)	The droplet is an ellipsoid, and the deformation and the maximum size difference of the droplet are considered
2014	Gang model (Gang 2014)	The droplet is an ellipsoid, and the influence of temperature and pressure on the interfacial tension is considered
2018	Jie model (Jie et al. 2018)	The droplet is an ellipsoid. The deformation of the droplet and its effect on the surface free energy of the droplet are considered

$$d = \frac{4(2K^3 + 4)\sigma v_{sl}}{3f_{sg}\rho_g v_{sg}^3 K} \quad (2)$$

In the above formula, K is the droplet deformation parameter, with the calculation formula ($K = d_E / d_B$), is the windward surface diameter of ellipsoidal droplet, d_B is the diameter of spherical droplet, m, and d is the windward surface diameter of droplet, m. When $K = 1$, d is the diameter of spherical droplet; when $K \neq 1$, d is the windward surface diameter of ellipsoidal droplet. v_{sl} and v_{sg} , respectively, show the apparent velocity of liquid phase and gas phase, m/s. σ represents the surface tension coefficient of gas–liquid interface, N/m. f_{sg} represents the surface tension coefficient of gas–liquid interface, N/m. ρ_g denotes the density of the gas, kg/m³.

Assuming that the horizontal section of the ellipsoid droplet is circular, the vertical section is elliptical, and the ellipsoid surface is smooth, as depicted in Fig. 1. Then, in the vertical wellbore, the ellipsoid droplet will be affected by buoyancy, drag and gravity simultaneously.

$$F_D + F_g - G = 0 \quad (3)$$

In the above formula, F_D denotes drag force, F_g denotes buoyancy, and G denotes gravity, N.

The drag force calculation formula is as follows:

$$F_D = \frac{1}{2} C_D S_E \rho_g v_c^2 \quad (4)$$

In the above formula, V_c is the critical liquid-carrying velocity, m/s. C_D is the drag coefficient. S_E is the windward surface area of the droplet, m², which can be expressed by the following formula (Jie et al. 2018):

Fig. 1 Schematic diagram of the model of spherical droplet changing into ellipsoidal droplet

$$S_E = \frac{4}{9} \pi \left[\frac{(2K^3 + 4)\sigma v_{sl}}{f_{sg}\rho_g v_{sg}^3 K} \right]^2 \quad (5)$$

However, under the combined action of various forces in the wellbore, the droplets not only move along the wellbore axis but also rotate. That is to say, the carrying effect of various forces on the droplets is not only transformed into the translational kinetic energy of the droplets, but also into the rotational kinetic energy of the droplets (Li et al. 2010; Awolusi, 2006; Na 2007; Sun et al. 2019b; Xiangguo et al. 2021). Assuming the droplet rotates uniformly along the Y-axis and the rotational angular velocity is w rad/s, the rotational kinetic energy is:

$$E_w = \frac{1}{8} m d_E^2 w^2 \quad (6)$$

Assuming that the droplet rises at a constant speed and the velocity is V_{CD} m/s, the translational kinetic energy of the droplet is:

$$E_D = \frac{1}{2}mv_{cD}^2 \quad (7)$$

The predecessors neglected part of the energy consumed by the droplet in rotation. That is to say, all the energy generated by the combined action of various forces on the droplet is converted into the translational kinetic energy of the droplet, which can be expressed by the following formula:

$$\frac{1}{2}mv_c^2 = \frac{1}{2}mv_{cD}^2 + \frac{1}{8}md_E^2\omega^2 \quad (8)$$

In other words, the critical carrying velocity V_C should be greater than the rising velocity V_{CD} of the droplet and can offset the energy consumed by the rotation of the droplet (Sun et al. 2018, 2017), so as to successfully carry the droplet out of the wellhead. Suppose that η is the liquid-carrying efficiency of the gas, then there exists the following equation:

$$\eta = \frac{v_{cD}^2}{v_c^2} = \frac{4v_{cD}^2}{4v_{cD}^2 + d_E^2\omega^2} \quad (9)$$

The rolling phenomenon of droplets during the process of lifting is common, the main reason is that the rising gas is not uniform and continuous, and the droplets are not evenly distributed in the wellbore. Also, the droplets are not standard ellipsoid or spherical, so the force on the droplets is not balanced, and the droplets will collide with the wellbore wall in the process of lifting, so the droplets will roll in the process of lifting. There are many influencing factors of droplet rolling, and the current research results can only qualitatively describe the phenomenon, but it is difficult to measure and quantify, so it can only be determined based on field experience. According to the related research of Li et al. (2010), the critical carrying velocity of droplet rolling is 1.996 times that of Li's model. Because Li's model does not consider the energy loss caused by droplet rolling, that is to say, the critical liquid-carrying velocity after droplet rolling is considered to be 0.5, η is about 0.5.

The formula of traction force after rolling is as follows:

$$F_D = \frac{1}{2}C_D S_E \rho_g v_{cD}^2 = \frac{1}{2}\eta C_D S_E \rho_g v_c^2 \quad (10)$$

Substituting the gravity calculation formula, buoyancy calculation formula and formula (10) into formula (3) yields:

$$\frac{1}{2}\eta C_D S_E \rho_g v_c^2 + \frac{1}{6}\pi d_B^3 \rho_g g - \frac{1}{6}\pi d_B^3 \rho_l g = 0 \quad (11)$$

where ρ_l is the density of mineralized water, kg/m³. Furthermore, by substituting formula (5) into the above formula (11) and simplifying it, we can obtain the model based on Pan's critical liquid-carrying velocity and consider the critical liquid-carrying velocity of gas after droplet rolling.

$$v_c = \frac{6.89K}{(K^3 + 2)\sqrt{\eta C_D}} \left(\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right)^{0.25} \quad (12)$$

Prediction model of liquid loading time in water-producing gas well

According to the critical liquid-carrying velocity of gas, the formula of critical liquid-carrying flux can be obtained as follows:

$$q_c = 2.5 \times 10^8 \frac{pA v_c}{ZT} \quad (13)$$

In the above formula, q_c represents the critical liquid-carrying capacity of gas, m³/D; A represents the cross-sectional area of flow channel, m²; p represents the wellhead pressure, MPa; Z represents the compressibility of gas; and T represents the thermodynamic temperature, K.

The classical production decline model (Wang et al. 2017, 2020) of Arps is as follows:

$$q = \frac{q_r}{(1 + bD_r t)^{1/b}} \quad (14)$$

In the above formula, q_r refers to the production of the gas well at the beginning of decline, m³/D. b denotes decline index, dimensionless. D_r denotes the decline rate, d⁻¹. t denotes the decline time, D.

Assuming that production rate of a gas well decreases to a certain extent, which is just the critical liquid-carrying capacity, the time (t_c) when the gas well decreases to the critical liquid-carrying capacity can be calculated.

$$t_c = \frac{\left(\frac{zTq_r}{2.5 \times 10^8 pA v_c} \right)^b - 1}{bD_r} \quad (15)$$

The model can be used to predict the possibility of fluid accumulation at different stages of gas production well.

Model comparison and field application

Comparison with Pan's model

(1) Analysis of the influence of droplet rolling on the critical liquid-carrying capacity

Table 1 shows that Pan's model is an ellipsoidal droplet model with comprehensive consideration at present. The proposed model in this paper is improved on the basis of Pan's model, so the model in this paper is compared with Pan's model. It is verified by the relevant calculation

parameters of a vertical gas well at which has been flooded in Moxilei-1 gas reservoir; relevant physical properties are collected in Table 2. In addition, the drag coefficient, deformation parameter, critical Weber number, surface tension considering the influences of pressure and temperature, and natural gas density are calculated as follows (Jie et al. 2018; Zhibin and Yingchuan 2012):

Drag coefficient C_D :

$$C_D = 0.36[1 + 2.632(K-1)] \quad (16)$$

Deformation parameters K :

$$We_c = \frac{16\pi \left(\frac{2+K^3}{3K} - 1 \right)}{7.951 - \frac{2.744}{K^2} + \frac{0.3077}{K} - 5.117K + 0.501K^2} \quad (17)$$

Weber number We_c :

$$We_c = \frac{5.14\rho_g v_{sg}^2}{\sigma} \sqrt{\frac{\sigma}{\rho_l g}} \left[15.4 \left(\frac{\sigma}{\rho_l v_{sg}^2} \sqrt{\frac{\rho_l g}{\sigma}} \right)^{0.58} + \frac{3.5G_{le}}{\rho_l v_{sg}} \right] \quad (18)$$

Surface tension σ :

$$\sigma(T_s) = \frac{1.8(137.78 - T_s)}{206} [\sigma(23.33) - \sigma(137.78)] + \sigma(137.78) \quad (19)$$

Natural gas density ρ_g :

$$\rho_g = 3484.4 \frac{\gamma_g P}{ZT} \quad (20)$$

In the above formula, $\sigma(T_s)$ is the surface tension of water at specific temperature, mN/m. γ_g is the relative density of natural gas. v_{sg} is the apparent velocity of gas phase, m/s. G_{le} is the mass flow rate of droplet, kg/(m² · s).

Then, according to the relevant calculation parameters in Table 2, the Pan's model and the model in this paper, the critical liquid-carrying flow comparison curves under different deformation parameters and rolling energy consumption can be obtained, as shown in Fig. 2. It can be observed that the closer the droplet is to the sphere, the greater the critical liquid-carrying capacity, and the more obvious the energy consumption caused by the droplet rolling. In addition, the more obvious the droplet rolling is, the greater the gas flow is needed to carry the droplet out of the wellhead.

And the more obvious the ellipsoid shape of the droplet is, the smaller the critical liquid-carrying capacity is, and the smaller the possibility of liquid accumulation is.

(2) Example comparison

The accuracy of this model and Pan's model is compared by using the example data. For the convenience of calculation and simple comparison between Pan's model and this model, assuming that the deformation parameter (K) is constant as 1.4, the drag coefficient (C_D) is 0.739. The relevant parameters and calculation results are shown in Table 3.

Case application: a case study of Moxilei-1 gas reservoir

(1) Prediction of critical liquid-carrying capacity

To verify the rationality of the model proposed in this paper, a vertical gas well A in Moxilei-1 gas reservoir is used for verification. The wellhead temperature T is 330 K, the average compressibility factor Z is 1.02, the inner diameter of tubing is 0.062 m, the relative density of natural gas is 0.65, and the mineralized water density is 1100 kg/m³. In addition, assuming the deformation parameter is a constant as 1.8, the drag coefficient is 1.118, and the comparison curve between the critical liquid-carrying flow rate and the actual flow rate of well A can be obtained (Fig. 3).

Fig. 2 Critical gas-carrying flow rate considering droplet rolling

Table 2 Relevant calculation parameters of critical liquid-carrying model

Relevant parameters in wellbore	Numerical value	Relevant parameters in wellbore	Numerical value
Average temperature $T(k)$	320	Relative density of natural gas γ_g	0.65
Average compression factor Z	0.82	Mineralized water density ρ_l (kg / m ³)	1100
Inner diameter of oil pipe (m)	0.062	Wellhead pressure P (MPa)	5

Table 3 Application comparison of this model and Pan's model

Serial number	Wellhead pressure (MPa)	Wellhead temperature (K)	Gas production ($10^4\text{m}^3/\text{d}$)	Production situation	This model ($10^4\text{m}^3/\text{d}$)	Pan's model ($10^4\text{m}^3/\text{d}$)
1	1.88	292.8	1.88	Close to liquid accumulation	1.41	0.99
2	2.2	291	3	Continuous liquid-carrying	1.52	1.08
3	16.3	293	3.4	Close to liquid accumulation	3.51	2.48
4	16.3	292.2	4.3	Continuous liquid-carrying	3.51	2.48
5	1.43	291	1.16	Liquid accumulation	1.24	0.87
6	10.5	292	2.8	Close to liquid accumulation	3.02	2.13
7	4	290.8	2.88	Continuous liquid-carrying	2.01	1.42

Figure 3 shows that the Pan's model predicts that the well has accumulated fluid at 2000–3000 days, but in fact, the well has not accumulated fluid in this period, and the timing for realistic fluid accumulation is about 3000 days. It is obvious that the model proposed in this paper is more reasonable than Pan's model.

(2) Prediction of gas well liquid loading time

According to this model, the critical liquid-carrying capacity of well A is calculated to be about $1.1 \times 10^4 \text{ m}^3$. The Arps decline equation is used to fit the historical production data over 2000 days, and the time when the gas production of the well decreases to the critical liquid-carrying capacity is predicted. Finally, it is compared with the actual gas production curve and the actual liquid accumulation time. The fitting and prediction results are shown in Fig. 4. The results are as follows: decline index $b=0.9$, decline rate $D_r=0.065 \text{ D}^{-1}$. The time of gas production decreasing to $1.1 \times 10^4 \text{ m}^3$ is close to 2913 d, that is, the possible start time of fluid accumulation in well

A is 2913 days, which is close to the actual time of fluid accumulation in well A of 3000 days. It indicates that this method can reasonably predict the time of fluid accumulation in gas wells in advance.

Summary and conclusions

1. During the rising process of the droplets in the wellbore of gas well, due to the unbalanced torque, the droplets keep rolling up and down, which consumes the energy of carrying liquid and reduces the efficiency of liquid loading. Considering the influence of droplet rolling, the new model is more reasonable than existed Pan's model.
2. Combined with Arps production decline equation and new critical liquid-carrying model, a prediction model of liquid loading time for water-producing gas wells is proposed. The model can accurately predict the possibility and timing of liquid accumulation at different production stages.

Fig. 3 Comparison of the prediction results of this model and Pan's model with the effusion time of well A in Moxilei-1 gas reservoir

Fig. 4 Prediction of accumulation time in well A by combining ARPS production decline equation and critical liquid-carrying flow rate

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References

- Awolusi O (2006) Resolving discrepancies in predicting critical rates in low pressure stripper gas wells. Master Thesis, Texas Tech University
- Beibei J, Haitao Li, Zhouzhou Y, Yusheng J, Tianqi Z (2013) A new method for optimization of drainage and production measures of water well in su59 block. *Oil Drill Prod Technol* 35(05):79–83
- Chaoyang P (2010) Study on the critical flow rate of liquid carrying in gas wells. *Xinjiang Pet Geol* 31(1):72–74
- Coleman SB, Clay HB, Mccurdy DG, Lii LN (1991) A New look at predicting gas-well load-up. *JPT* 43(3):329–333
- Desheng Z, Weipeng Z, Jianxun L et al (2014) Study on multi droplet model of fluid carrying in gas wells. *Hydrodyn Res Progress* 29(5):572–579
- Gang L (2014) A new method for calculating the critical flow rate of fluid carrying in gas wells. *Fault Block Oil and Gas Fields* 21(3):339–340
- Haitao Li (2017) Natural gas engineering. Petroleum Industry Press, Beijing
- Haitao L, Nianyin L (2019) Oil production engineering. Petroleum Industry Press, Beijing
- Jie P, WuJie W, Yaoqi W, Junbin C, Liangliang W (2018) Calculation model of critical liquid carrying velocity of gas well considering the influence of droplet shape. *Nat Gas Ind* 38(01):67–73
- Li HS, Hua LG, Zhi Y, Juan GY, Hao SY, Jing GX (2010) A new model for predicting fluid accumulation in low pressure gas wells. *Oil Gas Well Test* 19(05):9–13
- Li M, Sun L, Li S L. New view on continuous-removal liquids from gas wells. In: SPE Permian Basin Oil and Gas Recovery Conference. Midland, Texas, USA, Society of Petroleum Engineers, 2001: 1–6
- Min L, Lei S, Shilun L (2001) A new model of gas well continuous drainage. *Nat Gas Ind* 21(5):61–63
- Na W (2007) Visualization experimental study of gas well effusion. Southwest Petroleum University
- Rui W, Yun Ma, Liangbin D, Jiarui C, Ningsheng Z (2019) Research progress on critical fluid carrying and accumulation models of water producing gas wells. *Sci Technol Eng* 19(33):10–20
- Said Z, Sundar LS, Tiwari AK, Ali HM, Sheikholeslami M, Bellos E, Babar H (2021) Recent advances on the fundamental physical phenomena behind stability, dynamic motion, thermophysical properties, heat transport, applications, and challenges of nanofluids. *Phys Rep*
- Sheikholeslami M, Farshad SA (2021) Numerical simulation of effect of non-uniform solar irradiation on nanofluid turbulent flow. *Int Commun Heat Mass Transf* 129:105648
- Sheikholeslami M, Jafaryar M (2020) Nanoparticles for improving the efficiency of heat recovery unit involving entropy generation analysis. *J Taiwan Inst Chem Eng* 115:96–107

- Sun Z, Li X, Shi J, Zhang T, Sun F (2017) Apparent permeability model for real gas transport through shale gas reservoirs considering water distribution characteristic. *Int J Heat Mass Transf* 115:1008–1019
- Sun Z, Li X, Shi J, Zhang T, Feng D, Sun F, Li L (2018) A semi-analytical model for the relationship between pressure and saturation in the CBM reservoirs. *J Natl Gas Sci Eng* 49:365–375
- Sun Z, Shi J, Wu K, Zhang T, Feng D, Li X (2019a) Effect of pressure-propagation behavior on production performance: implication for advancing low-permeability coalbed-methane recovery. *SPE J* 24(02):681–697
- Sun Z, Wu K, Shi J, Zhang T, Feng D, Wang S, Liu W, Mao S, Li X (2019) Effect of pore geometry on nanoconfined water transport behavior. *AIChE J* 65(8):e16613
- Sun Z, Li X, Liu W, Zhang T, He M, Nasrabadi H (2020) Molecular dynamics of methane flow behavior through realistic organic nanopores under geologic shale condition: Pore size and kerogen types. *Chem Eng J* 398:124341
- Sun Z, Huang B, Li Y et al (2021) Nanoconfined methane flow behavior through realistic organic shale matrix under displacement pressure: a molecular simulation investigation. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-021-01382-0>
- Turner RG, Hubbard MG, Dukler AE (1969) Analysis and prediction of minimum flow rate for the continuous removal of liquids from gas wells. *JPT* 21(11):1475–1482
- Wang Ke, Li H, Wang J, Jiang B, Chengzhong Bu, Zhang Q, Luo W (2017) Predicting production and estimated ultimate recoveries for shale gas wells: a new methodology approach. *Appl Energy* 216:1416–1431
- Wang K, Jiang B, Li H, Liu Q, Chengzhong B, Wang Z, Tan Y (2020) Rapid and accurate dynamic reserves evaluation for different types of shale gas wells: production decline analysis methods. *Int J Coal Geol* 218:103359
- Xiangguo LU, Bao CAO, Kun XIE et al (2021) Enhanced oil recovery mechanisms of polymer flooding in a heterogeneous oil reservoir. *Pet Explor Dev* 48(1):169–178
- Zhibin W, Yingchuan Li (2012) Mechanism of continuous fluid carrying in gas wells. *Acta Pet Sin* 33(4):681–686

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