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# Modeling productivity of horizontal wells in a high sulfur gas reservoir: Consideration of the impact of porosity reduction by sulfur deposition

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## ABSTRACT

As pressure in a high sulfur gas reservoir drops during the development process, deposition of elemental sulfur in pores results in a decrease in porosity and permeability, which ultimately has an adverse effect on gas production.Using the relationship between element sulfur solubility and pressure, in tandem withthe theory of gas stable seepage,a mathematical model that explainselemental sulfur precipitation can be established. The model can befurther used to establish a horizontal well pseudo pressure productivity model, whichconsidersthe effect of sulfur deposition on permeability in a high sulfur gas reservoir.According to the field case study presented herein, use of the new model equationproduces a result that approximates the actual wellproductivity, which means that this model canbe used as apredictive tool for estimating productivity of a high sulfur gas reservoir that isbeing developed using horizontal wells.

**Keywords:** High sulfur gas reservoir; elemental sulfur deposition; pseudo pressureproductivity model; irreducible water; flow state.

## INTRODUCTION

Thedevelopment measure of high sulfur gas reservoirs is different from that of theconventional natural gas reservoirs due to the strong corrosivity and toxicity of H2S and the deposition of elementalsulfur. In the development process, the solubility of elemental sulfur in sour gas will decrease with the decline of reservoir pressure (Guo, 2016). Deposition of sulfur via sublimation will occur, and this solid phase sulfur may eventually reduce or entirely block the pores and pore throats in the reservoir,resulting from the further pressure drop as the reservoir fluid reaches a sulfur-saturated state and then the porosity and permeability of reservoir will be reduced(Kuo, 1972).

When compared with aconventional gas reservoir,a high sulfur gas reservoir has many factors that influence the inflow performance relationship (IPR) of a gas well in the reservoir. The key toeffective development of a high sulfur gas reservoiris to minimizehow these factors influence IPR,in the most economically feasible and reasonable way. During development of ahigh sulfur gas reservoir, the gas well absolute open flow potential and rational productivity is an important parameter, because it directly affects the feasibility of gas well recovery and the field scale of gas development. The productivity methods likeBorisov (1964), Giger (1984), Jourdan (1984), Joshi (1987), Lang (1993), and Chen (2008),based on constant effective permeability,are widely used in high sulfur gas reservoir. Because of this assumption of constant effective permeability, these methods are inadequate for use inconsideration of how sulfur deposition leads to damage and loss of porosity and permeabilityand as such, these methods are of less utility during development of a high sulfur gas reservoir.

Since 2005, Chinahas focused much effort on the development of high sulfur gas reservoirs, with many scientists and engineers working on research that investigates the influence of elemental sulfur deposition on productivity ofhorizontal wells in more detail, in particular the effect on productivityduringthe process of gas extraction from high sulfur gas reservoirs. Wang(2012) and Hu(2016) considered the effect of sulfur deposition on permeability, and their work established a productivity prediction formula that is applicable to development efforts relying on the use of horizontal wells. From this work, it was hypothesized that elemental sulfurdeposition and heterogeneity are the most important factors that controlhigh sulfur gas reservoirsproductivity. Dang(2013)successfully established strip high sulfur gas reservoir in the horizontal well production forecasting quasi three-dimensional formulas on the basis of famous Ji(2011) Formulaandanalyzedthe effect of sulfur deposition volume and the influence law of permeability anisotropy coefficient on production.

Hu (2016) improved the abovemodels(Borisov (1964), Giger (1984), Joshi (1987), Lang (1993), and Chen (2008)) via use of damaged effective permeability replaced byinitial effective permeability. But becausethese binomial pressure production models (Hu (2016) and Borisov (1964),and others) were built on assumed constant effective pressure, we hypothesize that use of damaged effective permeability should also be considered in the initial modeling process, rather than after the process is modeled. Therefore, we propose ahigh sulfur gas reservoir production formula that is built around consideration of pseudopressure, not binomial pressure, and that this model represents a major improvement over thefive classical models of Borizov (1964),and others. In this paper, the productivity prediction model of horizontal wells isbuilt by introducing the pseudo pressure function,which considers the damage to permeabilitythat is caused by deposition of elemental sulfur in the reservoir during development.Our comparison of results predicted by this new model with calculated day gas production of other four of the fiveclassical models (Borisov (1964), Giger (1984), Joshi (1988), and Chen (2008)) and with production well testing datafound that the new model provides a more accurate calculated result forproduction of gas from ahigh sulfur gas reservoir being developed with horizontal well techniques.

## SULFURSATURATIONANDRESERVOIR PERMEABILITY

This model assumed that elemental sulfur was not precipitated underthe conditions of original formation pressure and that migration of sites of sulfur deposition did not occur in the channel. It is only gas stable seepage.Elemental sulfur quality in gas is changed due to pressure dropping in solubility (dc) at r (radial distance). Precipitated sulfur quality can be expressed as

$$dm = 2\pi rh\phi(1-S_{wi})drdc \tag{1}$$

Sour gas reservoir pore volume:

$$dV_s = \frac{2\pi rh\phi(1-S_{wi})drdc}{\rho_s} \tag{2}$$

Elemental sulfur saturation:

$$dS_s = \frac{dV_s}{2\pi rh\phi dr} = \frac{(1-S_{wi})dc}{\rho_s} \tag{3}$$

Equation (3) is changed to

$$\frac{dS_s}{dp} = \frac{(1-S_{wi})}{\rho_s}\frac{dc}{dp} \tag{4}$$

Based on associative law and entropy principle, an empirical equation with Brunnerand Wollexperimental data is obtained(Roberts, 1997; Brunner and Woll, 1980).

$$\frac{dc}{dp} = 4(\frac{M_a\gamma_g}{ZRT})^4 \exp(\frac{-4666}{T} - 4.5711)p^3 \tag{5}$$

Combined with equations (4) and (5),

$$\frac{dS_s}{dp} = \frac{(1-S_{wi})}{\rho_s}4(\frac{M_a\gamma_g}{ZRT})^4 \exp(\frac{-4666}{T} - 4.5711)p^3 \tag{6}$$

In order to simplify this calculation,

$$A = \frac{(1-S_{wi})}{\rho_s}4(\frac{M_a\gamma_g}{ZRT})^4 \exp(\frac{-4666}{T} - 4.5711) \tag{7}$$

Equation (6) is changed to

$$dS_s = Ap^3dp \tag{8}$$

Equation (8) can be changed into (9) by integral.

$$S_s = \frac{A}{4}(p_i^4 - p^4) \tag{9}$$

because there is single-phase flow without considering water and precipitated sulfur flow.We thinkgas-phase permeability is treated as the reservoir effective permeability.

$$K = K_g = K_aK_{rg} \tag{10}$$

Elemental sulfur may precipitate when the reservoirpressure drops to critical pressureand given the negative effects of precipitated sulfur on reservoir permeability, an empirical equation (Roberts, 1997)about relative damaged permeability and sulfur saturation is provided:

$$K_{rg} = \exp(\alpha S_s) \tag{11}$$

Substituting variables and thencombiningequations (10) and (11) withequation (9), we obtain effective permeability of thereservoir,expressed as

$$K = K_a \exp(\frac{\alpha A}{4}(p_i^4 - p^4)) \tag{12}$$

## A HIGH SULFUR GAS RESERVOIR PRODUCTIVITY MODEL TO HORIZONTAL WELL ESTABLISHMENT

### Geological model

Assumption:

① Reservoir horizon, uniform thickness;
② Radial flow, ignore the effect of gravity on single-phase seepage;
③ Precipitated sulfur insitu deposit;
④ Isothermal reservoir.

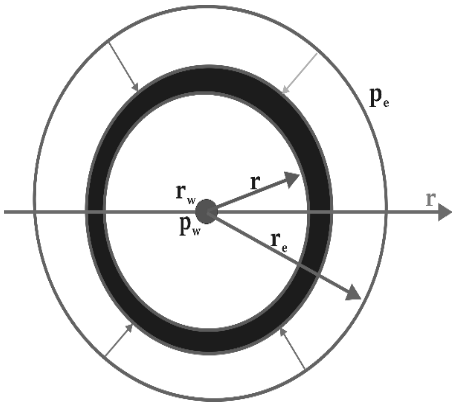


**Figure 1.** Plane radial flow model.

Gas radially inflows bottom hole, which is the plane radial flow model (Figure 1). But horizontal well pressure change has four stages from open well, which are (1) the initial radial flow (vertical radial flow), (2) the second stage initial radial flow, (3) the middle linear flow period, and (4) the late quasi radial flow (horizontal radial flow). Assuming that they better meet the seepage of actual formationand that the first three stages occur overa relatively short time, we can simplify the model such that a horizontal well is consideredto be influenced byonlyquasi radial flow during thelate stage. Duringextraction via drilling, the shape of the single well seepage field is an approximate elliptic. Introducing the concept of effective well radius(Joshi, 1988), we use the following equation:

$$r_{we}=\frac{r_{eh}(L/2)}{\left(\frac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right)\left(\frac{h}{2r_w}\right)^{\frac{\eta^2 h}{L}}} \tag{13}$$

where

$$a=\frac{L}{2}\left[0.5+\sqrt{\left(2r_{eh}/L\right)^4+0.25}\right]^{0.5} \tag{14}$$

$$\eta=\sqrt{K_h/K_v} \tag{15}$$

$$r_{eh}=\sqrt{r_{ev}\left(r_{ev}+L/2\right)} \tag{16}$$

**Horizontal well productivity model**

On the basis of the above assumptions of the geological model, and with proper consideration of when the gas flow into well borefrom the gas reservoir begins, the well section of perpendicular flow direction is closer to the well axis, and the sectional area is smaller; thus the velocity of the gas is predicted to increase sharply. By this time, the well shaft around the rapidly increasing flow of the gas is no longer following Darcy's Law, and the equivalent of turbulent flow, called the non-Darcy flow. So,non-Darcy flow should be considered in high sulfur production model.Therefore, Forcheimer (1901) proposed binomial non-Darcy flow equation as

$$\frac{dp}{dr}=\frac{\mu_g}{K}\frac{q}{2\pi rh}+\beta\rho_g\left(\frac{q}{2\pi rh}\right)^2 \tag{17}$$

And where is turbulence coefficient in 1/m, it can be gained (Li, 2001) as follows:

$$\beta=\frac{1.15\times10^7}{K\phi} \tag{18}$$

Gas density under the geological conditions:

$$\rho_g=\frac{M_a\gamma_g p}{ZRT} \tag{19}$$

Gas volume factor:

$$B_g=\frac{P_{sc}}{Z_{sc}T_{sc}}\frac{ZT}{p} \tag{20}$$

The production under the geological conditions is transformed into production under the ground condition, wherein

$$q=Q_{sc}B_g=Q_{sc}\frac{P_{sc}}{Z_{sc}}\frac{ZT}{p} \tag{21}$$

Substituting equations (19) into (21), we obtain plane radial flow yielding to differential form:

$$Kpdp=\frac{Q_{sc}p_{sc}ZT\mu_g}{2\pi hT_{sc}}\frac{1}{r}dr+\frac{3.33\times10^6Q_{sc}^2p_{sc}^2TZ\gamma_g}{4\pi^2h^2T_{sc}^2R\phi}\frac{1}{r^2}dr \tag{22}$$

In order to simplify the calculation, and are the constant when there are calculated. Substituting equations (12) into (22), and the integral, we obtain

$$\int_{p_w}^{p_e}K_a\exp\left(\frac{\alpha A}{4}(p_i^4-p^4)\right)pdp=\int_{r_{we}}^{r_e}\frac{Q_{sc}p_{sc}ZT\mu_g}{2\pi hT_{sc}}\frac{1}{r}dr+\int_{r_{we}}^{r_e}\frac{3.33\times10^6Q_{sc}^2p_{sc}^2TZ\gamma_g}{4\pi^2h^2T_{sc}^2R\phi}\frac{1}{r^2}dr \tag{23}$$

Let

$$\varphi(p)=\int\exp\left(\frac{\alpha A}{4}(p_i^4-p^4)\right)pdp \tag{24}$$

Equation (23) is derived:

$$\varphi(p_e)-\varphi(p_w)=\frac{Q_{sc}p_{sc}ZT\mu_g}{2\pi hK_aT_{sc}}(\ln r_e-\ln r_{we})+\frac{3.33\times10^6Q_{sc}^2p_{sc}^2TZ\gamma_g}{4\pi^2h^2T_{sc}^2K_aR\phi}(\frac{1}{r_{we}}-\frac{1}{r_e}) \tag{25}$$

Let

$$\mathrm{D}=\frac{p_{sc}ZT\mu_g}{2\pi hK_aT_{sc}}(\ln r_e-\ln r_{we}) \tag{26}$$

$$E=\frac{3.33\times10^6p_{sc}^2TZ\gamma_g}{4\pi^2h^2T_{sc}^2K_aR\phi}(\frac{1}{r_{we}}-\frac{1}{r_e}) \tag{27}$$

Then, equation (25) is changed to

$$\varphi(p_e)-\varphi(p_w)=DQ_{sc}+EQ_{sc}^2 \tag{28}$$

Equation (28) used the extract roots formula; we obtain

$$Q_{sc}=\frac{-D+\sqrt{D^2+4E\left(\varphi\left(p_e\right)-\varphi\left(p_w\right)\right)}}{2E} \tag{29}$$

Finally,barefoot completionhorizontal wells productivityin high sulfur gas reservoirhas been got inequation (29), which considers the effect of sulfur deposition on permeability.

## THECLASSIC MODEL OF HORIZONTAL WELL

Borisov (1964) model:

$$Q_{sc}=\frac{0.2714\times Kh\left(p_e^2-p_w^2\right)}{\ln\left(\frac{4r_{eh}}{L}\right)+\frac{h}{L}\left(\frac{h}{2\pi r_w}\right)}\frac{T_{sc}}{\mu_gZTp_{sc}} \tag{30}$$

Giger (1984) model:

$$Q_{sc}=\frac{0.2714\times Kh\left(p_e^2-p_w^2\right)}{\ln\left(\frac{1+\sqrt{1-\left(L/2r_{eh}\right)^2}}{L/2r_{eh}}\right)+\frac{h}{L}\left(\frac{h}{2\pi r_w}\right)}\frac{T_{sc}}{\mu_gZTp_{sc}} \tag{31}$$

Joshi (1988) model:

$$Q_{sc}=\frac{0.2714\times Kh\left(p_e^2-p_w^2\right)}{\ln\left(\frac{a+\sqrt{a^2-\left(L/2\right)^2}}{L/2}\right)+\frac{\beta^2h}{L}\left(\frac{\left(h/2\right)^2+\eta^2}{0.5hr_w}\right)}\frac{T_{sc}}{\mu_gZTp_{sc}} \tag{32}$$

Chen (2008) model:

$$Q_{sc}=\frac{0.2714\times Kh\left(p_e^2-p_w^2\right)}{\ln\left(\sqrt{\left(\frac{4b}{L}-1\right)^2-1}\right)+\frac{h}{L}\left(\frac{h}{2r_w}\right)}\frac{T_{sc}}{\mu_g ZTp_{sc}} \tag{33}$$

where

$$b=\frac{L}{4}+\sqrt{\left(\frac{L}{4}\right)^2+r_{eh}^2} \tag{34}$$

## CASE CALCULATION AND ANALYSIS

Ahigh sulfur gas in Sichuanwill be used as our example to illustrate howcan the model be of importance in predicting the behavior of sulfur during production of the gas. According to the gas well test report, the parameters areshown in Table 1.

**Table 1.** Basic parameters of the sour gas well.

| Basic parameters | Value |
|---|---|
| Reservoir (K) | 427.15 |
| Reservoir initial pressure(MPa) | 68.50 |
| Reservoir porosity(%) | 9.8 |
| Reservoir absolutepermeability (μm$^2$) | $4.36\times10^{-3}$ |
| Gas relative density | 0.645 |
| Gas average viscosity(Pa·s) | $3.52\times10^{-5}$ |
| Irreducible water saturation | 0.24 |
| Reservoir thickness(m) | 51.3 |
| Sulfur density(kg/m$^3$) | 2070 |
| Z-factor | 1.3719 |
| Gas reservoir radius(m) | 1000 |
| Well radius(m) | 0.08255 |
| Horizontal well production length(m) | 682.8 |

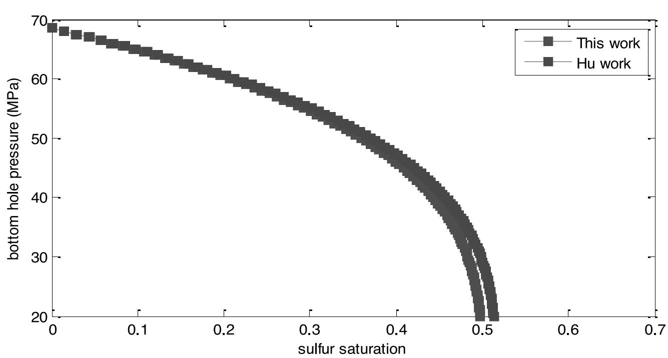


**Figure 2.**Comparison of bottom hole pressure vs. sulfur saturation under themodel presented here and the model of Hu (2013).

This new sulfur deposition model (equation (10)) was verified bycomparing it with the model of Hu (2013), as shown in Figure 2, and this comparison demonstrates that the two models both provide a very close and reasonable trend of the findings. It shows that new built sulfur deposition model is correct. We have made a lot of optimization in the model derivation ofHu (2013). The establishing and solving method was significantly improved, contributing to a more clearer representation onthe effect of pressure drop on sulfur deposition.Furthermore,the new established pseudo pressure productivity model based on it is also reasonable.We selected part of this well testing data (Table 2) for comparison with calculated data of this new model and with the fouradditionalmodels, as shown in Figure3. From this comparison, it can be seen in Figure3 that this new model, which takes sulfur deposition into consideration, is closerto the production data. Because the new model takes into account the effect of sulfur deposition on the reservoir effective permeability,other four classic modelsdidnot consider it, which leads to the result thatcalculation deviates from the actual data.Sothe four classic modelsare deemed to be no longer suitable for modeling the behavior of a high sulfur gas reservoir. At the same time, the effect of sulfur deposition on open flow potential was analyzed via the Borisov (1964) model (Figure4) and as seen in Figure4, sulfur deposition has anegative effect on production of high sulfur gas reservoir. Effective permeability was replaced by equation (12) when we made the calculations using theBorisov model to ensure a more accurate consideration of sulfur deposition.The production equation is as regards pseudopressure but binomialpressure when effective permeability changes with pressure changing. So, the Borisov (1964)model cannotcalculateaccurately the production from ahigh sulfur gas reservoir because it fails to accuratelyconsider the negative effects the deposition of elemental sulfur has on the porosity and permeability of the reservoir.

**Table 2.** Well testing data.

| **Bottom hole pressure (MPa)** | **Day gas production ($10^4m^3/d$)** |
|---|---|
| 58 | 115.23 |
| 56 | 140.54 |
| 54 | 155.35 |
| 52 | 168.44 |
| 50 | 185.21 |
| 48 | 192.74 |

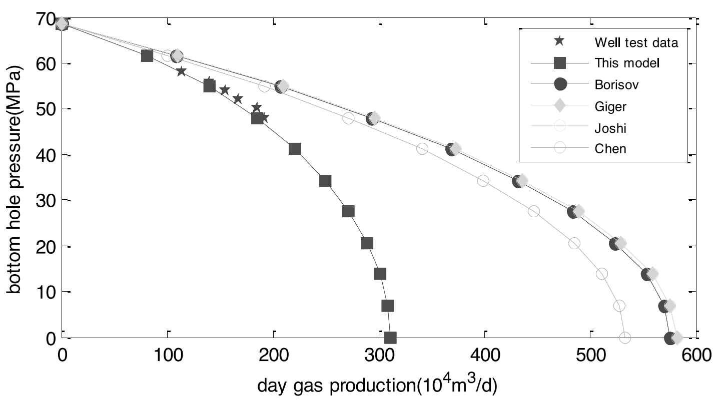


**Figure 3.** The IPR under different models.

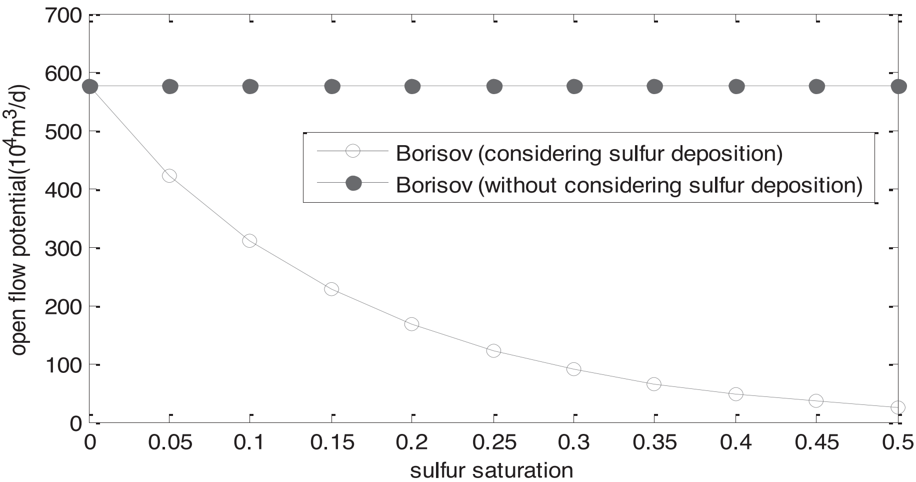


**Figure 4.** The effect of sulfur deposition on open flow potential of Borisov (1964) model.

**The effect of irreducible water on IPR**

Figure5presentsthe relationship between irreducible waters onIPR (equation (29)). It can be seen that day gas production is increasing with irreducible waterdecreasing when bottom holepressure is constant.Thebigger the irreducible water, the bigger the sulfur saturation (Figure6) and the smaller the effective permeability (Figure7), resulting in smaller day gas production (Figure5). When the bottom hole pressure is 40MPa, as the irreducible water increases from 0.1 to 0.2, the value of sulfur saturation and effective permeability,respectively,increases by 18.75% and 27.6%, and the value ofday gas production decreases by 5.39%.Therefore, irreducible water has an influence on IPR.

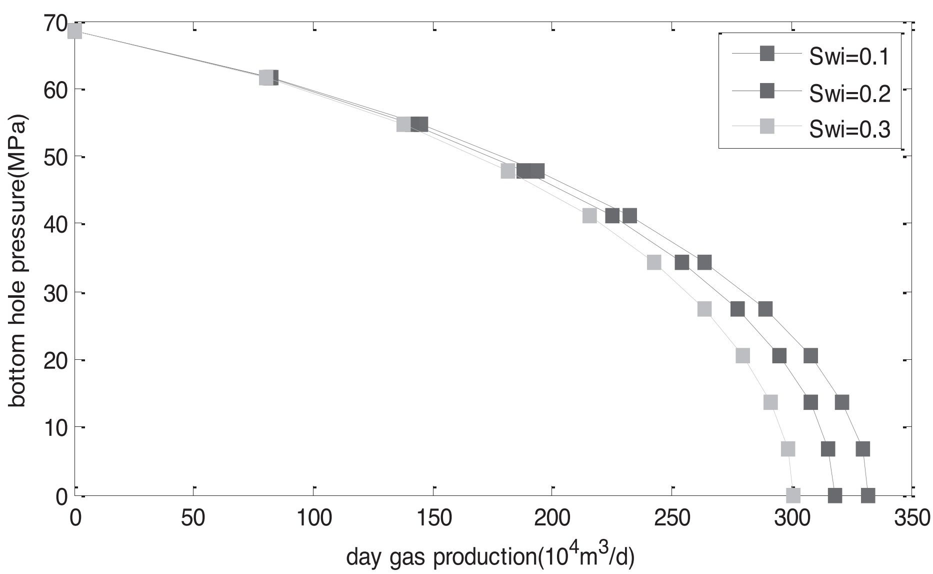


**Figure 5.** The effect of irreducible water on IPR.

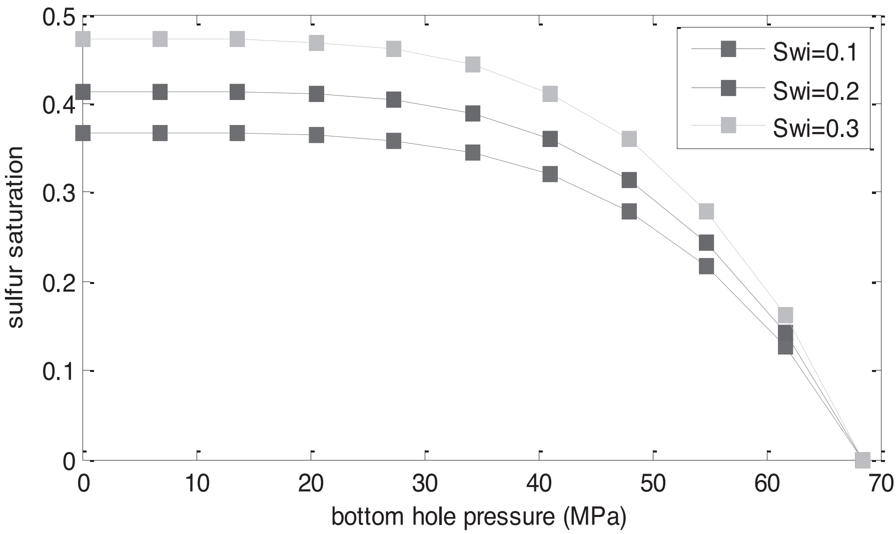


**Figure 6.** The effect of irreducible water on sulfur saturation.

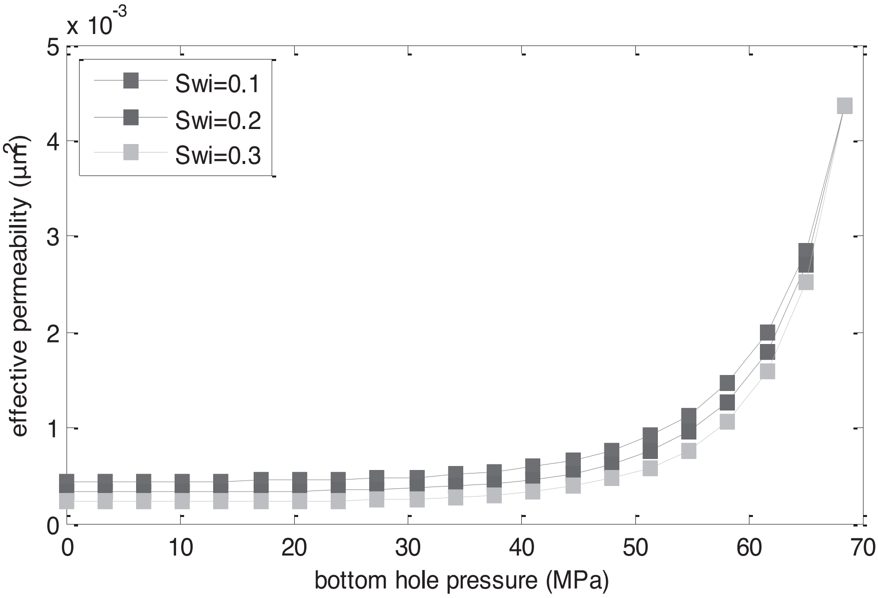


**Figure 7.** The effect of irreducible water on effective permeability.

**The effect of flow state on IPR**

Figure8 is the relationship between flow state on IPR.It can be seen that day gas production increasesasbottom hole pressure decreases. For a constant day gas rate production, the required production pressure difference of non-Darcy is smaller than Darcy flow. Because additional pressure loss should be considered for the non-Darcy flow;meanwhile the energy lossincreases, with the gas velocity increasingnear the wellbore zone. Therefore, the effect of non-Darcy flow should be considered whenproduction from ahigh sulfur gas reservoir is being modeled. In addition, we suggest that it is beneficial to accurately predict the day gas production of well.

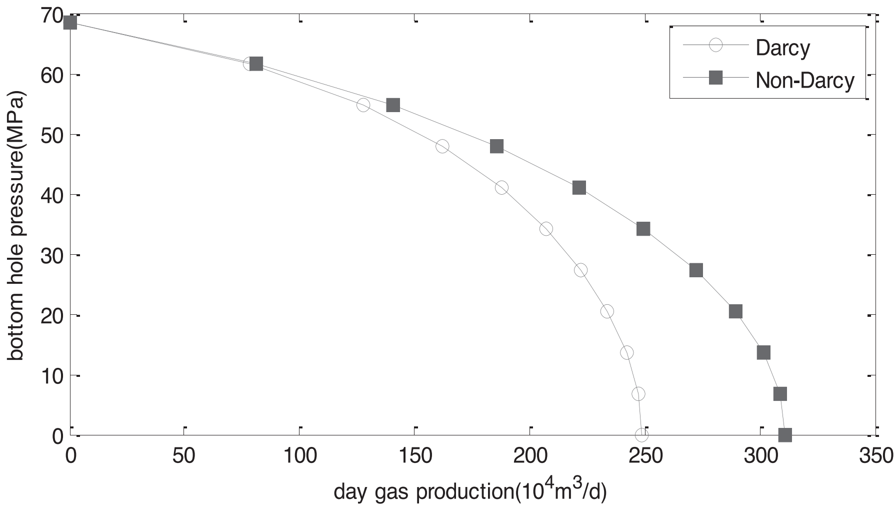


**Figure 8.** The effect of flow state on IPR.

## CONCLUSION

Tomodel production of gas from a well that is completed in a high sulfur gas reservoir, the effect of deposition of elemental sulfur on gas productionneeds tobe considered, because it always has a negative impact on the porosity and permeability of the reservoir over time. The pseudo pressure productivity modelpresented herein is better able tocalculateproductionof gas from horizontal wells completed in a high sulfur gas reservoir. Four classical binomial pressure productivity models (Borisov (1964), Giger (1984), Joshi (1988), and Chen (2008)) are less effective at accurately modeling gas production from such reservoirs and as such areno longer considered to be suitable for modeling of production from a high sulfur gas reservoir. In addition, the more volumethe irreducible water, the bigger the sulfur saturation and the smaller the effective permeability, resulting in less day production of gas. Additional pressure loss should be considered for the non-Darcy flow;meanwhile the energy loss increases with the gas velocity increases near the wellbore zone. So, for a constant day gas rate production, the required production pressure difference of non-Darcy is smaller than Darcy flow.

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## NOMENCLATURE

| | |
|---|---|
| $m$ | solid sulfur quality, kg/m$^3$; |
| $h$ | reservoir thickness, m; |
| $\phi$ | reservoir porosity; |
| $r$ | radius of gas reservoir, m; |
| $c$ | sulfur solubility, kg/m$^3$; |
| $V_s$ | solid sulfur volume, m$^3$; |
| $\rho_s$ | density of the solid sulfur, 2070 kg/m$^3$; |
| $S_s$ | sulfur saturation in porous media; |
| $S_{wi}$ | irreducible water saturation; |
| $p_i$ | initial gas reservoir pressure, MPa; |
| $p$ | pressure of gas reservoir, MPa; |
| $p_e$ | boundary pressure, MPa; |
| $p_w$ | bottom hole pressure, MPa; |
| $M_a$ | molecular weight of the dry air, 28.97; |
| $\gamma_g$ | relative density of natural gas; |
| $Z$ | deviation factor of natural gas; |
| $R^*$ | conventional gas constant, 0.008315; |
| $L$ | horizontal well horizontal length, m; |
| $K$ | effective permeability, μm$^2$; |
| $K_a$ | absolute permeability,μm$^2$; |
| $K_{rg}$ | relative permeability,μm$^2$; |
| $K_h$ | horizontal formation permeability,μm$^2$; |
| $K_v$ | verticalformation permeability,μm$^2$; |
| $\alpha$ | 6.22; |
| $\mu_g$ | fluid viscosity,; |
| $q$ | gas well production, m$^3$/d; |
| $B_g$ | gas volume factor, m$^3$/ m$^3$; |
| $P_{sc}$ | standard state pressure, 0.101325 MPa; |

$Z_{sc}$ standard state gas Z-factor, 1;

$T_{sc}$ standard statetemperature, 293 K;

$T$ reservoir temperature, K;

$Q_{sc}$ standard state production, $m^3/d$;

$r_e$ drainage radius, m;

$r_w$ well radius, m;

$r_{eh}$ drainage radius of horizontal well, m;

$r_{ev}$ drainage radius of vertical well, m;

$r_{we}$ effective radius of horizontal well, m;

$\eta$ square root of permeability ratio;

$a$ half the major axis of drainage ellipse, m.

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# نمذجة إنتاجية الآبار الأفقية في خزان غاز عالي الكبريت: النظر في تأثير خفض المسامية عن طريق ترسب الكبريت

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قسم مختبر الدولة الرئيسي لجيولوجيا واستغلال خزان النفط والغاز، تخصص هندسة تطوير حقول النفط والغاز، جامعة ساوث ويست للبترول، تشنغدو، 610500، الصين.

## الخلاصة

عندما ينخفض الضغط في خزان غاز مرتفع في نسبة الكبريت أثناء تطوير طرق الانتاج، يؤدي ترسب الكبريت في المسام إلى انخفاض في المسامية والنفاذية، والذي يكون له في النهاية تأثير عكسي على إنتاج الغاز. وباستخدام العلاقة بين قابلية ذوبان عنصر الكبريت والضغط، جنباً إلى جنب مع نظرية تسرب الغاز، يمكن إنشاء نموذج رياضي يفسر ترسب عنصر الكبريت. ويمكن استخدام هذا النموذج أيضاً لإنشاء نموذج يوضح إنتاجية الضغط الكاذب لبئر أفقي، والذي يأخذ في الاعتبار تأثير ترسب الكبريت على النفاذية في خزان غاز عالي الكبريت. ووفقاً لدراسة الحالة الميدانية هذه، تُظهر المعادلة الجديدة للنموذج نتيجة تعمل على تقريب الإنتاجية الفعلية للبئر، مما يعني أنه يمكن استخدام هذا النموذج كأداة تنبؤية لتقدير إنتاجية خزان غاز عالي الكبريت يتم تطويره باستخدام الآبار الأفقية.