A Novel Strategy Dealing with Producing Period in Low Pressure Gas Wells

DOI : 10.36909/jer.17899

Fei Wang
School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, China
Oil and Gas Equipment Technology, Sharing and Service Platform of Sichuan Province, Chengdu, China
(Email: wangfei_swpu@126.com; Corresponding Author)

Yanrong Yang
School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, China (Email: 1491638236@qq.com)

Liang Li
Central Sichuan Oil and Gas District, PetroChina Southwest Oil & Gas field Company, Suining, China
(Email: lilcz@petrochina.com.cn)

Qianlin Yang
Department of Railway Engineering, Sichuan College of Architectural Technology, Chengdu, China (460266545@qq.com)

Abstract

Low-pressure gas wells are of increasing interest to the petroleum industry as economic and environmental importance of natural gas continues to grow. To maximize the production of low permeability gas reservoir, a novel production strategy to determine reasonable producing periods, including the pressure draw down process and the pressure build up process, in low pressure gas wells has been investigated. Additionally, the variation of down-hole pressure and gas flow in both processes were considered to formulate the optimization model to find reasonable switching times for low-pressure gas wells in this research. In order to enhance the adaptability of the production strategy proposed in this research, parameters of erosion flow rate, critical flow rate of liquid loading and reasonable differential producing pressure of the reservoirs were considered in the proposed mathematical model which aims at maximizing gas production of low-pressure gas wells. Based on the application of the mathematical model dealing with reasonable production strategy

of low-pressure gas wells, the pressure of gas well varies smoothly in both shut-in process and gas production process when the novel production strategy was applied. And nature gas production of the gas well increases dramatically compared with that before.

Keywords: producing period; low pressure gas wells; optimization model; gas production period; gas well shut-in period

1. Introduction

Natural gas, as a very important source of energy and chemical feedstock, can be used in place of coal and oil to lower carbon dioxide emissions. The low-pressure gas wells, whose gas productions are much smaller, are of increasing interest to the petroleum industry as the economic and environmental importance of natural gas continues to grow. However, the recoverable reserve of natural gas has decreased a lot in recent years and many low pressure gas wells even cease producing economically long before their reservoirs have been depleted. Many researchers focus on the problem of the liquids loading in low pressure gas wells. Turner and Coleman estimated the minimum flow rate for the continuous removal of liquids form gas wells (Turner et al., 1969; Coleman et al., 1991). Tang et al have studied the methods of preventing the liquids loading in low pressure gas wells (Tang, 2009; Xiao and Ahmad, 2004; Whitson et al., 2012). Lea et al investigated the liquid lift technologies such as gas lift, former injection, small-ID tubing, flow controllers and submersible pumps (Lea and Nickens, 2004; William, 2010). To attain a good recovery efficiency in low permeability reservoirs, many methods of determining reasonable producing period in minor production oil wells have been applied and economic benefits in those oil wells have been improved (Nita, 2013; Lima, 1997; Richard and Walter,1999; Aiting et al., 2016). However, few publications have been found concerning to the approaches of producing period determination in low pressure gas wells, which might be useful for maximizing the recoverable production in low permeability gas reservoirs.

The present research aims at investigating a method for determining the reasonable producing periods in low pressure gas wells.

2. Governing Equations for low pressure gas wells

Nomenclature

p_r	average pressure of the gas reservoir	η	diffusion coefficient of formation
p_f	bottom hole pressure	γ	relative density of gas
Q	gas flow rate	r_w	radius of gas well
A	cross section area of the tubing	ρ_m	mixture density of the flow
K	permeability of formation,	ρ_G	density of the natural gas
h	thickness of formation	ρ_L	density of the liquids
σ_L	surface tension of the liquids	Q_{sc}	flow rate under standard conditions
p_{sc}	pressure under standard conditions	μ_i	fluid viscosity of gas in reservoir
T_i	temperature in reservoir	T_{sc}	temperature under standard conditions
Z_i	gas compressibility factor under reservoir condition	Z_{sc}	compressibility factor of gas under standard conditions

For a given set of gas reservoir conditions, the ability of delivering a certain quantity of natural gas in the reservoir depends directly on the flowing bottom-hole pressure. Researchers presented an empirical relationship between them which has been frequently used in reservoir deliverability analysis (Boogar and Masihi, 2010; Brage and Bjarne, 2013). In low pressure gas reservoirs, the relationship can be mathematically expressed in terms of pressure squared as

$$Q = c\left(p_r^2 - p_w^2\right)^n \tag{1}$$

Exponent c and n are numerical coefficient and characteristic in particular gas wells. In this equation mentioned above, if the exponent c and n were determined, then the gas flow rate, Q, may be evaluated at any bottom-hole pressure and the inflow performance relationship can be prepared.

The pressure and deliverability in the low-pressure gas wells would apparently decline along with the gas production. Although the drawing down process of pressure runs for a long time, it has not been used extensively to evaluate gas reservoirs for the reason that a constant rate is needed in that test. According to the analysis done by Wattenbarger, reasonable results could be obtained when the seepage differential equation was expressed in terms of pressure squared (Wattenbarger, 1968), and the non-Darcy's law flow is more likely to occur in low permeability gas reservoirs. Then, the bottom-hole flowing pressure of the gas wells, located at low pressure reservoir, can be simplified by the usual approximations as

$$p_{wf} = \sqrt{p_r^2 - \frac{Q_{sc} p_{sc} T_i \mu_i Z_i}{2\pi K h T_{sc} Z_{sc}} \log \frac{4\eta T_o}{\gamma r_w^2}} \tag{2}$$

Here, T_o is the producing time of the gas well.

Equation 2 describes the drawing down process of the pressure in a gas well where the gas reservoir around is neither damaged nor improved. If the condition of permeability damage or improvement exists in the gas well, an additional term must be added to the equation to account for these effects. Thus, Equation 2 becomes

$$p_{wf} = \sqrt{p_r^2 - \frac{Q_{sc} p_{sc} T_i \mu_i Z_i}{2\pi K h T_{sc} Z_{sc}} \left(\ln \frac{4\eta T_o}{\gamma r_w^2} + 2S_a \right)} \tag{3}$$

Where S_a is the skin factor which could be obtained by the test curve of the gas well.

By inserting the pressure draw down Equation (3) into the Equation (1), the gas flow rate, after the gas well has produced for time T_o, could be given by

$$Q_{sc1} = c^{\frac{1}{1-n}} \left[\frac{p_{sc} T_i \mu_i Z_i}{2\pi K h T_{sc} Z_{sc}} \left(\ln \frac{4\eta T_o}{\gamma r_w^2} + 2S_a \right) \right]^{\frac{n}{1-n}} \tag{4}$$

Here, Q_{sc1} is the gas flow rate during the deliverability draw down period.

As to the deliverability build up process when the well shut in, Horner showed that a plot of the shut-in pressure versus $log((T_o+T_s)/T_s)$ would result in a straight line for an infinite acting reservoir (Knudsen and Foss, 2013; Sun et al., 2015). If the gas well was shut-in for a time T_s and its producing time is expressed as T_o, the bottom hole static pressure builds up at time T_s by the principle of superposition can be obtained with acceptable accuracy as

$$p_{ws} = \sqrt{p_r^2 - \frac{Q_{sc} p_{sc} T_i \mu_i Z_i}{2\pi K h T_{sc} Z_{sc}} \ln \frac{T_o + T_s}{T_s}} \tag{5}$$

Then, by substituting Equation (5) into Equation (1) and rearranging the equation, the flow in the gas reservoir, after the gas well has been shut-in for a time T_s, can be obtained as

$$Q_{sc2} = c^{\frac{1}{1-n}} \left[\frac{p_{sc} T_i \mu_i Z_i}{2\pi K h T_{sc} Z_{sc}} \left(\ln \frac{T_o + T_s}{T_s} \right) \right]^{\frac{n}{1-n}} \tag{6}$$

Here Q_{sc2} is the gas flow during the deliverability build up period.

As the tubing might be damaged due to erosion when the gas well is produced at a higher rate, the production should be controlled by the maximum erosion velocity allowed. To eliminate erosion losses, it is recommended in the publication API RP 14E that the maximum flow rate in the system be limited to a value, Q_{eros}, defined by the following empirical equation (Behery et al., 2010; Nan et al., 2015),

$$Q_{eros} = 5.164 \times 10^4 A \left(\frac{p_{sc}}{Z_{sc} T_{sc} \gamma} \right) \tag{7}$$

Liquid loading or accumulation, which will impose an additional back-pressure on the gas formation and might completely water flood the well in low pressure gas reservoir, occurs when the gas phase does not provide adequate energy for the continuous removal of liquids from the well bore. Therefore, the liquids in the well bore, which come from condensation of hydrocarbon gas or from interstitial water in the reservoir matrix, must be transported to the surface by the gas flow. After a careful analysis of the physical models for the removal of gas well liquids and testes based on field data, Turner found that the minimum condition required to unload liquid accumulated in gas well is that which will move the largest liquid droplets that exist in a gas stream. And the critical flow rate for a gas well to remove the liquids can be obtained as,

$$Q_{crit} = 1.59 A \sqrt[4]{\frac{\sigma_L \left(\rho_L - \rho_L \right)}{\rho_G^2}} \tag{8}$$

Besides, according to the existing production gas wells, edge water or bottom water exists in most gas reservoirs. And if the exploration of the gas well is taken unreasonably, the water flooding will easily emerge as gas reservoir is always pressure sensitive. Prorating differential pressure between the bottom flowing pressure and the average pressure of the gas reservoir too high or too low, can lead a series of problems such as energy loss, reservoir damage, and bottom effusion, thus will lower the gas productivity and affect the development benefit. According to the production experiences, the differential pressure should not exceed 10% of the average pressure of the gas reservoir. Thus, by substituting the expression of the differential pressure, $\Delta p = p_r - p_{wf}$, into Equation (1) and simplifying the equation, the differential pressure can be approximately obtained as in Equation (9).

$$\Delta p = c^{-\frac{1}{n}} Q_{sc}^{\frac{1}{n}} \frac{1}{2p_r} \tag{9}$$

3. Optimization model of the producing period

According to the investigations on the low-pressure gas wells which have been producing gas for several decades in China, the pressure of these low-pressure gas wells decreases quickly within few hours during the draw down process and the pressure builds up again in the next few hours when the gas wells were shut in. Besides, these gas wells are shut in or opened manually and most of these gas wells locate more than 30 minutes' ride from gathering station. Considering the pressure variations and management of these low-pressure gas wells, the major assumptions are made as follows,

- The reservoirs to be considered are the closed loop gas reservoirs, and the pressure disturbance could spread to the boundaries of the reservoirs.
- The seepage in the reservoir is assumed as unsteady flow.
- The effects of the natural gas stored in the well bore are neglected.
- The minimum producing period of the gas wells is controlled as 6 hours for the convenience of gas well management.

As mentioned above, the general gas producing procedures in low pressure gas wells involve the deliverability draw down process and build up process. And the variation of the bottom-hole pressure and flow rate in these two processes could be shown as in Figure 1.

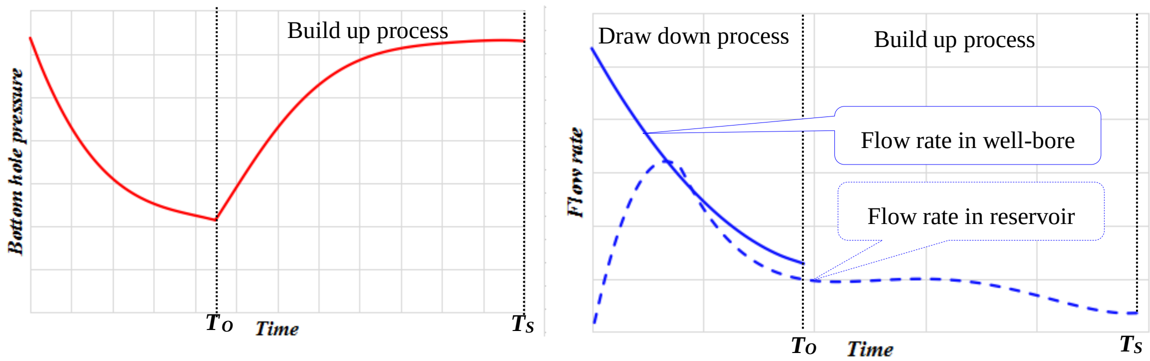

Figure 1 Variation of bottom-hole pressure and flow rate in low pressure gas wells

Due to the elastic release of compressed natural gas at the early period of the draw down process, the flow rate in gas reservoir increase dramatically with time which is contrary to the variation tendency of bottom hole pressure and flow rate in well-bore.

According to the objective described above, the producing period includes the deliverability draw down process and the deliverability build up process, the problem of finding the optional switching times in each producing period for gas wells can be formulated as following,

$$\text{Maximize} \quad \sum_{i=1}^{k} Q_i = i\left(\int_{o}^{T_O} Q_{sc1}dt + \int_{T_0}^{T_O+T_S} Q_{sc2}dt\right) \tag{10}$$

$$\text{Subject to} \quad T = T_O + T_S = \frac{24}{k}, \quad k=1, 2, 3, 4$$

$$Q_{sc2}(t) \le Q_{eros}$$

$$Q_{sc1}(t) \ge Q_{crit}$$

$$p_r - p_{ws} \le \Delta p$$

$$p_{wf} \ge p_{wf0}$$

Here k is the producing frequency of the gas well per day and p_{wf0} is the minimum bottom hole flowing pressure that the gathering system needed.

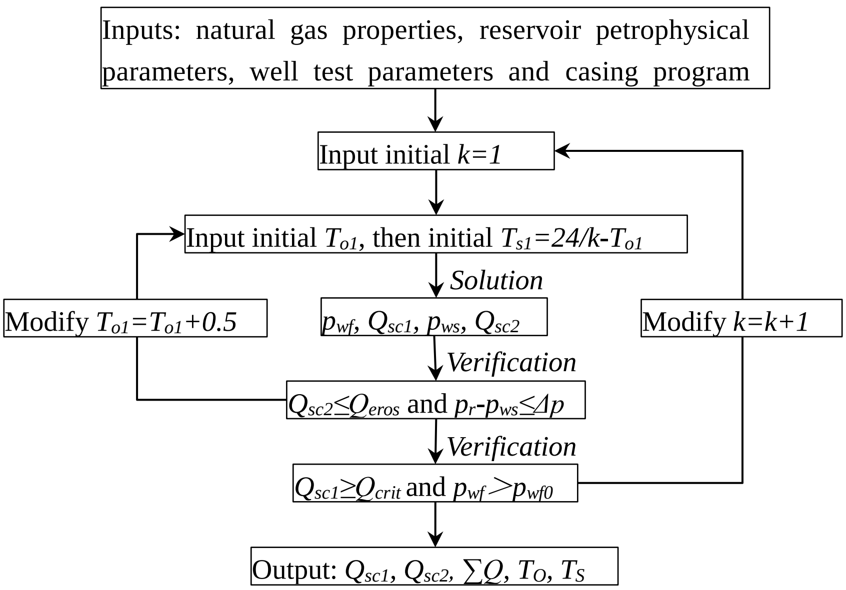

Figure 2 Flow scheme for producing period calculation

The flow scheme for producing period calculation has been shown in Figure 2. To determine the producing period for each low-pressure gas wells, a series initial producing times of the gas well T_O (or the shut-in time T_S of the gas well) is assumed form 0 hour to T with an increment of 0.5hour. Then, the parameters needed in the optimization model mentioned above should be calculated until the model is satisfied.

4. Example applications

To illustrate the optimization model proposed in this article, an actual low-pressure gas well, located at the southeast of Shengli oil field in China, is selected. And the method of determining the producing period has been applied on this gas well.

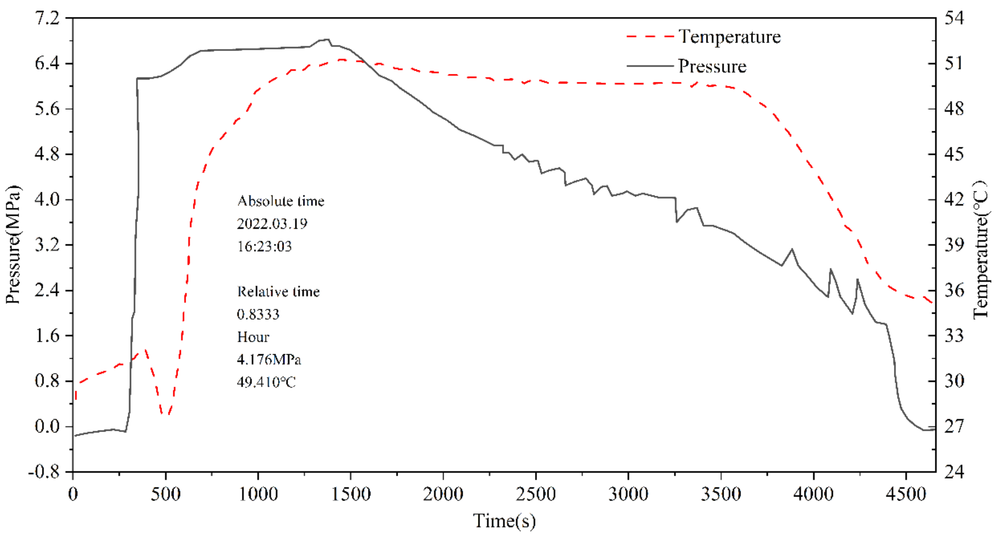

Figure 3 Pressure variation of the gas well when it starts to produce gas

The selected gas well has been put into production since year of 1985 with the depth is 940.2m, and the porosity of reservoir is 6.3%. The pressure of the gas reservoir is decreasing gradually after years of production. The gas well has a gas production of 1300m^3/d with its tubing pressure stayed at 2.1MPa and the casing pressure stayed at 1.7MPa. According to the pressure test operation in the bottom hole, shown as in Figure 3, the pressure drops sharply after the gas well starts to produce natural gas. Besides, shown as in Figure 4, the liquids removed from the gas well laminated and had subsidence after a 16 hours static settlement. Apparently, the gas reservoir has damaged caused by the series of work-over operations of gas wells.

Figure 4 Liquid samples lifted out from the gas well

According to the optimization method proposed in this article, the deliverability draw down process (in which the gas was produced) and the deliverability build up process (in which the gas well was shut in) are determined as 4.5 hours and 7.5 hours, respectively. Thus, the gas would produce natural gas two times per day and each period of production would cost 12 hours. Besides, the actual times of the producing gas could be determined according the operation system of different companies. In this application example, the gas well is producing gas from 6:00am to 10:30am and form 6:00 pm to 10:30pm, while the gas well is being shut in for deliverability build up in the rest of time. During the application of the method, the liquids in the well bore are lifted and the natural gas production has been increased by 43.6% compared with continuously production strategy used before (no shut-ins). Moreover, the tubing pressure varies smoothly in each process during the application of the method, shown as in Figure 5. The successful application of the producing strategy mentioned above indicates that it may extend the stable production period of the low-pressure gas well by using the method proposed in this article.

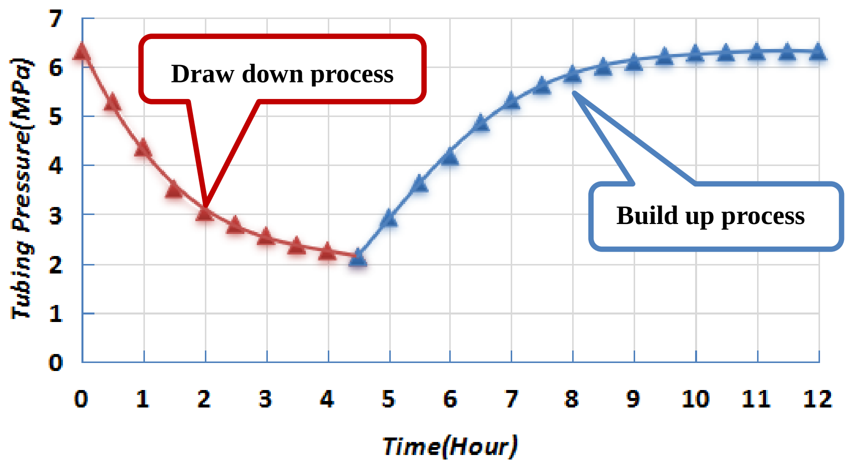

Figure 5 Variation of the tubing pressure in one period of production

To verify the feasibility of the proposed strategy dealing with producing period in gas wells in this article, the proposed mathematical method has been applied on another 7 actual low-pressure gas wells to determine the optimal producing and shut-in times of the selected intermittent gas wells, shown as in Table 1.

Table 1 Parameters of the selected intermittent gas wells

Gas well	Production allocation (10^4m^3)	Casing pressure (MPa)	Tubing pressure (MPa)	Production ($10^4m^3/a$)	Producing rate (%)
Z 2X-2	1.5	5.56	7.60	182.2	48.5
Y 3X-2	0.5	5.20	10.04	95.9	49.7
Y 4X-8	0.5	5.84	8.90	137.3	65.9
Z X	0.5	5.04	5.22	70.2	38.4
Y 4X-9	0.5	5.10	8.22	64.5	42.5
Z 2X-7	0.2	5.00	5.96	35.0	40.8
Z 2X-4	0.3	4.86	8.80	84.9	61.3

According to the pressure build up test and draw down test of these selected gas wells, the build-up periods and shut-down periods were initially determined as 30h and 40h respectively in this article to obtain the optimal producing strategy of the selected gas wells. By applying the proposed method in this article, shown as in Table 6, the optimal producing time, T_o, and shut-in time, T_s, have been determined for each selected gas wells.

Table 2 Optimal producing strategies of selected gas wells

Gas well	Production ($10^4m^3/d$)	Pressure build up rate (MPa/d)	Producing strategy ($h(T_s)$-$h(T_o)$)	Increased gas production (15d)	Production increase rate (%)
Z 2X-2	0.8313	0.1357	24-72	3.1658	66.5
Y 3X-2	0.5274	0.0503	48-24	1.6411	100.7
Y 4X-8	0.4537	0.1246	48-24	1.0532	20.6
Z X	0.5496	0.1007	24-72	1.9477	185.8
Y 4X-9	0.2687	0.1851	24-48	1.5747	52.1
Z 2X-7	0.3989	0.1620	24-48	0.7378	315.9
Z 2X-4	0.3007	0.1093	24-48	0.9862	29.3

Shown as in Table 2, after the producing strategy proposed in this article has been applied on the selected gas wells, the intermittent gas wells produce gas smoothly and the production of these gas wells increase significantly. Compared with the production of these gas wells before, the production of the selected intermittent gas wells increases at least 29.3%. And the production of gas well Z 2X-7 even increased more than 3 times compared with that before.

According to the application of the optimization model proposed in this research, petroleum engineers could maximize the production of low permeability gas reservoir. It is anticipated that the mathematical model and optimal control method proposed in this research may enhance the efforts of engineers in designing more reliable gas production strategy and, therefore, more sustainable production of low-pressure gas wells.

5. Conclusions

An optimization model was formulated to determine the reasonable producing period in low pressure gas wells, including the deliverability draw down process when producing gas and deliverability build up process when the well was shut in. Based on the work done above in this article, following results and conclusions can be reached:

(1) The main object of the approach is to determine the optional switching times for low pressure gas well in both gas production period and gas well shut-in period.

(2) The erosion flow rate, critical flow rate of liquid loading and reasonable producing differential pressure of the reservoirs are involved in the research.

(3) The tubing pressure of the selected gas well, in which the method proposed in this research applied, varies smoothly and the gas production has increased dramatically.

Acknowledgment

The authors would like to acknowledge the support by scientific research starting project of SWPU (No. 2017QHZ010), China.

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