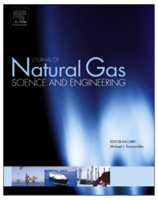
Journal of Natural Gas Science and Engineering 34 (2016) 159–169

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse



Critical drawdown pressure of sanding onset for offshore depleted and water cut gas reservoirs: Modeling and application

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ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form
1 May 2016
Accepted 23 June 2016
Available online 25 June 2016

Keywords:
Reservoir pressure depletion
Water cut
Sand production
Critical drawdown pressure

ABSTRACT

Offshore gas reservoirs are generally exploited without energy supplement, reservoir pressure depletion will cause rock stress changes, and water cut will also weaken rock cementation, which results in an increasing likelihood of serious sand production in the unconsolidated sandstone reservoir. This paper aims at offshore unconsolidated sandstone gas reservoirs, analyzes rock stresses of the borehole wall with impact of reservoir pressure depletion on in-situ stresses and water cut on rock strength. Combining with fully-polyaxial rock failure criterion Mogi-Coulomb, a new sanding critical drawdown pressure (CDP) calculating model and a numerical calculating method for the model are developed. Furthermore, an applicable sanding prediction method for pressure depletion and water cut offshore gas reservoir in well whole life cycle is proposed. The model was applied in DF gas reservoir in South China Sea, the chart of sanding CDP for well DF-A in the whole production life cycle was plotted. The research results indicate: Initially, the sanding CDP is relatively large, with formation pressure depletion, CDP is reduced step by step until depleted to the critical reservoir pressure, and sand will be produced no matter how small the drawdown is. Once water cut occurs, sanding CDP is furtherly decreased by 15%–20%. The research outcomes are consistent with actual oilfield production situation, which can provide some theoretical supports for sand production gas wells.

1. Introduction

Sand production is a universally encountered issue during the exploitation of unconsolidated sandstone reservoirs (Selby and Ali, 1988; Nouri et al., 2006; Ranjith et al., 2013). During well completion, production and workover, sand production may occur. Particularly, it is an offshore unconsolidated gas reservoir that is generally exploited with not enough or no energy supply, its formation pressure gradually drops, and if water invasion takes place simultaneously, the geological condition becomes even worse. Besides, the high speed gas flow generates a high drag force and can easily drag free sand particles into the wellbore, which will cause a more serious sanding onset (Vaziri et al., 2002b, 2004). A series of hazards will be caused by sanding, such as scouring casing, wearing production equipment, increasing the times of downhole sand washing and decreasing the output. Severe sand production can result in the tubing pump stuck, the wellbore buried, and even the production of gas wells stopped (Ohen, 2003; Volonté et al., 2010; Nwabueze et al., 2012). Sand production is closely related to production drawdown pressure except reservoir factors. In view of this, to prevent the risk caused by sand production for the offshore depletion and water cut gas wells, the key is to make a sand production prediction in advance and determine when and how to adjust the production drawdown pressure, which mitigates or eliminates the sand production to prevent and treat the sanding effectively.

At present, sand production prediction mainly employs field observation, empirical evaluation, laboratory test and numerical simulation method (Vaziri et al., 2002a): ①Field observation is to judge whether sand production or not by observing the unconsolidated extent of cores directly (Lu et al., 2002). This method is simple and applicable for the case that the prediction accuracy of sand production is not very demanding; ②Empirical evaluation, based on well logging data and rock mechanics test, applies acoustic wave travel time Δt_c (95 μs/ft < Δt_c < 105 μs/ft, slight

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http://dx.doi.org/10.1016/j.jngse.2016.06.057
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sanding; $\Delta t_c \geq 105$ μs/ft, serious sanding), combination modulus E_c (1.5×10^4 MPa $< E_c \leq 2.0 \times 10^4$ MPa, slight sanding; $E_c \leq 1.5 \times 10^4$ MPa, serious sanding), sanding index B ($B \leq 2.0 \times 10^4$ MPa, sanding), or schlumberger's ratio R ($R \leq 5.9 \times 10^7$ MPa^2, sanding) to predict whether the formation is sanding onset or not. This technique is simple, practically and commonly used in oilfield (Zhou et al., 1997; Lu et al., 2002); ③Laboratory test is to simulate wellbore and production conditions, and conduct flowing experiment to determine whether to produce sand or not (Selby and Ali, 1988). Now, the widely used experimental evaluating model is a thick walled hollow cylinder (TWC) model (Geertsma, 1987; Van den Hoek et al., 2000), Which can assess sandstone initial destruction, but unable to evaluate the stability of expansion after the destruction of the hole, and does not focus on the impaired or broken reservoir rock by perforation near wellbore; ④The numerical simulation method is to launch the dynamic coupling numerical model between rock mechanics and fluid mechanics, and determine the critical production drawdown pressure and critical flowing velocity of liquid-solid coupling in the sandstone layer (Morita et al., 1989a; Morita and Fuh, 1998; Cook, 2001; Wang and Lu, 2001; Volonté et al., 2010). The reservoir physical properties and many input parameters are not easy to be obtained, such as geological mechanics and rock mechanics parameters required, and the analytical process is rather complicated and time-consuming. For calculating sanding CDP, the Morita model (Morita et al., 1989a,b), empirical model CDP=(0−1) × UCS (Fjær et al., 1992) and Vaziri model (Vaziri et al., 2004) are usually applied. Nevertheless, the Vaziri model and Morita model did not consider interaction between water and rock, and the empirical model needs a mass of statistics of sanding data about large number of wells.

The above sanding prediction and CDP calculation methods mainly aimed at initial production period of gas wells, without considering impact of pressure depletion and water cut in the middle or later stage of production. But the impact of pore pressure depletion and water cut cannot be ignored (Vaziri et al., 2002b). Furthermore, field experience also shows that numerous gas formations had high strength in the early stage, even if their production was high, they did not produce sands at the initial stage. However, in the later stage of exploitation, the reservoir pressure energy is not effectively supplemented, formation pressure is gradually depleted, and the stresses exerting to borehole wall rock are increased, then the formation begins to produce sands, and sanding becomes more and more serious (Bruno et al., 1996; Lou and Liu, 2006; Ranjith et al., 2013). Also, water invasion can result in clay swelling and dispersion, and capillary force of the rock changes, which can greatly reduce reservoir rock strength (Vaziri et al., 2002b; Ohen, 2003), then rock is broken and particles are transported out, and large quantities of sands produce continually. Therefore, it is particularly significant to calculate CDP timely and make actual production drawdown pressure less than CDP in the later stage of production for the water cut and depleted unconsolidated reservoir, which enables to control sanding onset, avoid the sanding hazards and improve the productivity.

Currently, By Uniaxial Compressive Strength (UCS) or Thick Wall Cylinder (TWC) experiment, Palmer and Higgs (2005), Ispas et al. (2005), Rahman et al. (2008), Bai et al. (2012) and Chong and Chan (2013) built geological mechanical model of oilfield, analyzed the relationship between reservoir pressure depletion and borehole collapse, and established CDP for sanding on the reservoir with pressure depletion. Palmer and Higgs (2005), Ispas et al. (2005) and Rahman et al. (2008) calculated the borehole tangential stress $\sigma_{\theta\theta}$ to determine whether the well produces sands or not after reservoir pressure drops, then gave out CDP by $\sigma_{\theta\theta} \geq$ UCS. While Bai et al. (2012) calculated CDP according to CDP $= n \times$ UCS (n = 0−1). Nevertheless, these studies have not highlighted impact of water cut on sanding onset, and CDP calculation method can be improved further.

The unconsolidated offshore gas reservoir DF is located in the South China Sea. The reservoir has normal pressure and high geothermal gradient with initial pressure coefficient of 1.0−1.14 g/cm^3 and 4.17°C/100 m respectively. The pressure has been gradually depleted and water invasion occurs along with production, and sand production is a serious problem. This paper aims at DF gas field, based on analysis of stresses on borehole wall rock and optimization of criterion for rock failure, presents a new calculating model of CDP with considering variation of in-situ stress with formation pressure depletion and reduction of rock strength after water cut. A numerical method is proposed to carry out calculating CDP model for sanding of gas wells in whole life cycle. Thereby CDP and its chart of sanding for gas wells during different production stage can be obtained, which provides a theoretical basis for production proration of gas wells in DF gas reservoir.

2. Calculation model of sanding CDP

2.1. Mechanism and process of sanding when rock mass failure occurs

The formation sands can be divided into free sands and rock matrix sands. Free sands are in formation pore and can be easily dragged into wellbore with fluids. Because a quantity of free sands in the pore is relatively small, this sort of sands will not bring serious problems. When formation rock near wellbore is subjected to high concentration stress, and once critical instability condition of borehole wall is achieved, rock failure occurs and is broken into pieces, the pieces of rock mass fall off and are transported into wellbore, which will drain bulk of sands continuously and bring serious hazards to production (Tronvol et al., 1992; Morita et al., 1989b, c; Doi et al., 2000).

The failure of rock arises gradually from borehole wall to the interior of formation. Initially, shear failure of rock mass takes place at the stress concentration point around borehole wall where largest stress concentration exceeds the rock strength, resulting in small sanding cavity emergence. And then the rock of the cavity's surface wall will begin to break out at the stress concentration point again. This process is recurrent. In this case, small sanding cavity will increasingly grow bigger and bigger, gradually shaping big sanding cavities to the interior of formation, which can cause accumulation of volume and mass of sand debris into wellbore. The process of rock failure, and then sanding is as shown in Fig. 1.

2.2. Critical drawdown pressure model when rock mass failure occurs

To determine the critical condition of the borehole wall rock failure, the analysis of the borehole wall stresses (as seen in Appendix A) and selection of proper rock failure criterion should be focused on, and then adopt proper bottomhole flowing pressure to maintain stability of the borehole wall. Several rock failure criteria have been developed to investigate failure behavior of rock. Among these criteria, Mohr-Coulomb criterion (Jaeger and Cook, 1979), Hoek-Brown criterion (Hoek and Brown, 1980), Drucker-Prager criterion (Drucker and Prager, 1952), Modified Lade criterion (Ewy, 1999) and Mogi-Coulomb criterion (Al-Ajmi and Zimmerman, 2005) are commonly applied. The comparison of different rock failure criteria can be observed in Table 1.

Mohr-Coulomb criterion is the classical failure criterion of rock and most frequently used. Its hypothesis is that shear failure will take place when maximum shear stress on shear plane is equal to