Journal of Natural Gas Science and Engineering 27 (2015) 284–289

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

A closed form mathematical model for predicting gas temperature in gas-drilling unconventional tight reservoirs

Jun Li [a], Boyun Guo [b], Ben Li [b,*]

[a] China University of Petroleum-Beijing, China
[b] University of Louisiana at Lafayette, USA

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
27 August 2015
Accepted 27 August 2015
Available online 2 September 2015

Keywords:
Gas-drilling
Temperature
Prediction
Unconventional
Reservoirs

ABSTRACT

Drilling wells with gas, or gas-drilling, is a technique traditionally used to drill mining boreholes, geothermal wells, and conventional oil and gas wells. It has recently been adopted to drill shale gas wells and proven to be cost-effective in the United States. However, the performance of gas drilling is very unpredictable in many areas due to the lack of proper design of drilling parameters because of limited knowledge of gas–rock interactions. Complete analysis of gas–rock interaction requires a mathematical model to accurately predict gas temperature at bottom hole. Such a mathematical model is not available for gas-drilling. An analytical model was derived in this study to fill the gap. The analytical model is a closed form equation for predicting bottom hole gas temperature under various flow conditions. The result given by the analytical model was verified by a numerical model developed in this study. The difference between the two models was found to be less than 0.1%. A sensitivity study was carried out to identify possible sources of error when the analytical model is applied to real gas-drilling condition.

1. Introduction

Air, nitrogen, and natural gas are widely used as the working fluid in drilling mining boreholes, geothermal fluid wells, and oil and natural gas recovery wells (Lyons et al., 2001). This technique is referred to as gas-drilling. The rate of penetration (ROP) is usually more than 10 times higher in gas-drilling than in liquid-drilling (drilling with water, mud, or oil). However, the performance of gas-drilling is highly inconsistent in many areas. This is generally attributed to rock failure mechanism involving thermal effect.

Moore (1958) documented five factors that affect rock failure and thus drilling rate. The primary rock failure mechanism was identified as the mechanical action of drill bit teeth that causes wedging, scraping and grinding, and crushing of rock. The secondary rock failure mechanism was believed to be the erosion by fluid jet action (Bourgoyne et al., 1986). These mechanisms do not explain why the rate of penetration increases as the bottom hole pressure decreases. A number of technical documents have addressed the effects of confining stress and fluid pressure on rock failure (Murray and Cunningham, 1955; Cunningham and Fenink, 1959; Black and Green, 1978) in liquid-drilling. It has been commonly recognized that reducing bottom hole pressure can significantly increase ROP. This is because the low-level bottom hole pressure causes high-level unbalance of stress in the rock, making the rock softer and easier to break down under the mechanical action of drill bit teeth. The effect of bottom hole pressure on rock failure seems to explain the extremely high rate of penetration in gas-drilling (Sheffield and Sitzman, 1985; Li et al., 2006; Wang et al., 2008).

Zhang et al. (2012) presented their results of analytical and numerical modelling which reveal that gas-cooling to the bottom hole rock is another mechanism of rock failure in gas-drilling. It indicates that a rock layer of about 1.2 cm thick is under failure condition due to the cooling effect. Li et al.'s (2012a) experimental data demonstrates that this thermal effect drops when gas flow rate increases. This was interpreted as the gas "penetration" effect that pushes the temperature gradient inside the rock body. The mechanism of cooling failure of rock was verified by Zhang et al.'s (2014) experimental work that shows that the cooling effect can increase rate of penetration by 30%. Field observations also support the hypothesis of thermal failure of rock during gas-drilling. It has been found that drill cuttings collected from gas-drilling are much smaller than that from liquid-drilling. A comparison of drill cuttings collected from gas-drilling and liquid-drilling at similar depths in

* Corresponding author.
E-mail address: benli2596@gmail.com (B. Li).

http://dx.doi.org/10.1016/j.jngse.2015.08.064
1875-5100/

the same region showed a very significant difference (Li et al., 2013a). The drill cuttings collected from gas-drilling are dust-like, which are at least thousand-times smaller than the drill cuttings from liquid-drilling. The explanation to this fact is still controversial. Some researchers believe it due to the re-grinding of large cuttings at the bottom hole in the gas-drilled wells (Guo and Ghalambor, 2012). However, re-grinding would significantly reduce the rate of penetration, which does not seem to occur in gas-drilling. Another explanation is the theory of cuttings-crashing by drill string and other cuttings during their flowing up the borehole annulus (Li et al., 2013a). This is possible owing to pipe vibration when the drill string rotates at high speed. Crashing can occur between drill pipe and borehole wall, turbulent flow of fluids, uneven borehole gauge, doglegs, etc. The significance of the cuttings-crashing has not been well investigated. Li et al.'s (2013b) work indicates that the energy required to crash cuttings from 6 mm to 1 mm is nearly equal to the energy required to transport the cuttings from bottom hole to surface, which is considered to be not realistic. A reasonable explanation is that the cuttings created by the drill bit are much smaller than 6 mm. A portion of the dust-like cuttings are created at the bottom hole due to the fictional heating effect, or thermal failure of rock. This effect is similar to the weathering effect where the temperature at the surface of rock alters rapidly, causing the fast failure of rock surface, generating small sands. If this is the case, the cuttings size should depend on the level of frictional heat generated at bit teeth. High level of frictional heat should promote generation of fine cuttings. According to the theory of frictional heat generation (Kulehytsky-Zhihailo and Evtushenko, 1999; Evtushenko and Pauk, 2002), the heat flux is proportional to the contact pressure (stress). The contact pressure between drill bit and rock is higher at deep depth than that at shallow depth in gas-drilling. This is because low weight on bit is used to drill soft rocks at the shallow depth with high-rate of penetration and high weight on bit is used to drill hard rocks at the deep depth to maintain high-rate of penetration. As the weight on bit increases with depth, the contact stress (weight on bit divided by bit tooth contact area) increases, and thus the frictional heat increases. It is therefore expected that the size of drill cuttings decreases with depth. Li et al. (2012b) demonstrate the trend of change of cuttings size with depth. As the well deepens, the proportion of large-size cuttings drops and that of small cuttings increases. This trend of cuttings size change may be explained by three principles: 1) rock drillability drops with depth, 2) more cuttings-collision in deep holes, and 3) more thermal failure of rock in friction-heated deep/hard formations. The fact that cuttings are much finer in gas-drilling than in liquid-drilling at the same depth tends to support the principle of thermal failure more than the other two principles. Li et al. (2014) provides a comprehensive analysis of the thermal effect in gas-drilling. They concluded that the thermal failure process is complicated by the interference between the frictional heating and Joule-Thomson cooling to the rock surface. The Joule-Thomson cooling can promote or inhibit the thermal failure of rock at the bottom hole, depending on its degree of influence on the frictional heating. Increasing weight on bit and rotary speed will promote thermal failure of rock, but may damage drill bit due to over-heating. Adding water to the gas stream to protect the drill bit will cool down the rock, reduce the thermal failure of rock, and thus lower the rate of penetration. The thermal failure should be more pronounced in drilling shale gas formations because shale has lower tensile strength than sandstones. Obviously, in order to optimize gas-drilling parameters using the thermal effect, it is very essential to be able to predict the gas temperature at the bottom hole.

A number of researchers have investigated the methods for predicting fluid temperature profiles in drilling circulation systems. Among them are Zhang et al. (2011), Hasan and Kabir (2012), are Kutasov and Eppelbaum (2015). Unfortunately, all these methods were developed for liquid-drilling, not for gas-drilling. The only method for gas-drilling is the numerical simulator developed by Wang et al. (2007). The paper was published in a Chinese journal and the simulator is not accessible to the authors.

An analytical solution was derived in this study to solve the problem. The result given by the analytical solution was verified by a numerical model developed in this study. A sensitivity study with the analytical solution was carried out to identify possible sources of error when it is applied to real gas-drilling condition. Application of the newly developed analytical solution is illustrated in this paper.

2. Mathematical model

Accurate prediction of gas temperature at bottom hole depends largely on the ability of calculating the heat transfer during gas flow from surface to drill bit inside the drill string. An analytical model for steady heat transfer inside the drill string is derived in Appendix A. The model is briefly summarized in this section.

Major assumptions made in the model derivation include:

1) The thermal conductivities of drill pipe, cement column, and formation rock are assumed to be infinitive, i.e., gas in the annulus behaves as an insulation layer.
2) Heat capacity of gas is constant.
3) Friction-induced heat inside the drill string is negligible.

The thermal conductivities of steel drill pipe, cement concrete, sandstone rock, and air at 50 °C are 43 W/m- °C, 1.7 W/m- °C, 3 W/m- °C, and 0.03 W/m- °C, respectively. The high contrast (>50) in the thermal conductivity values makes the gas in the annular space the dominating material (limiting step) for the heat conduction in the radial direction. This also results in the natural geothermal gradient at the sand face practically not affected by the gas in the annulus. Therefore, the first assumption is valid.

Heat capacity of air is a function of temperature and pressure (Abbott and van Ness, 1989). In the temperature range between 0 °C and 100 °C at atmospheric pressure, the heat capacity of air varies between 1005 J/kg-C and 1009 J/kg-C, or within 0.40%. In gas-drilling operations the gas pressure in the drill string is in a narrow range between 7 MPa and 10 MPa. The heat capacity of air varies between 1016.2 J/kg-C and 1021.6 J/kg-C, or within 0.53%, in this pressure range (Kadoya et al., 1985). Considering the extreme condition of 0 °C and 10 MPa, the heat capacity of air varies between 1005 J/kg-C and 1021.6 J/kg-C, or within 1.65%, which justifies the second assumption.

All gases used in gas-drilling are dilute gases in the above-mentioned ranges of pressure and temperature. Gas density varies from 1 to 100 kg/m^3 and gas viscosity changes from 13.3×10^{-6} m^2/s to 22.1×10^{-6} m^2/s (Kadoya et al., 1985). The friction pressure drop in the whole circulation system is 15 MPa at most, with the friction pressure drop inside the drill string being less than 5 MPa over a few thousand meters of length. This low pressure drop is not expected to generate significant amount of heat, and thus the third assumption is valid.

The analytical solution for steady heat transfer in the drill string is expressed as follows:

$$T_f = \frac{1}{\alpha^2}\left[\beta - \alpha\beta L - \alpha\gamma + e^{-\alpha(L+C)}\right]. \tag{1}$$

where