Journal of Natural Gas Science and Engineering 28 (2016) 587–593

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Optimal design of jet mill bit for jet comminuting cuttings in horizontal gas drilling hard formations

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form
18 December 2015
Accepted 18 December 2015
Available online 23 December 2015

Keywords:
Horizontal gas drilling
Cuttings accumulation
Jet mill bit
Jet comminution
Cuttings size reduction

ABSTRACT

Gas drilling is considered as an ideal technique for drilling horizontal wellbore in hard formations. However, due to the low cuttings-carrying energy of gas in horizontal gas drilling, drill cuttings returned to surface are dusk-like, and the large cuttings not only can't be circulated out of down hole in time but also can't be reground by the bit teeth as in vertical gas drilling do. As a result, they are easily accumulated in the horizontal wellbores, which may lead to accidents such as wellbore plugging and pipe sticking. Based on jet comminution technique, a new type of bit called jet mill bit (JMB) was presented and optimal designed in this research, it provides a promising solution to the problem by comminuting cuttings into dust-like scale right after the cuttings are generated. In order to promote the optimal design and execution of the JMB, analytical models were developed for predicting the required cutting's impact velocity and designing the minimum length of accelerating tube in JMB, meanwhile the factors affecting the optimal design of JMB were also investigated. Case study using field data in the published article shows good consistency is observed between the predicted result and field experience. It is also concluded that the required cutting's impact velocity and the minimum length of accelerating tube increase with the initial cuttings size and decrease with the final cuttings size, and they decrease slowly with the final cuttings size when the final cuttings sizes larger than approximately 0.3 mm. This paper provides drilling engineers with a promising technology to eliminate cuttings accumulation in horizontal gas drilling.

1. Introduction

Gas drilling is defined as an operation of drilling wells with gas including air, nitrogen, and natural gas. Compared to liquid drilling, gas drilling can increase rate of penetration (ROP) over ten times. Therefore it is considered as an ideal technique for drilling horizontal wells in hard formations where the available weight on bit (WOB) and thus ROP are low. However, unlike conventional mud drilling, gas drilling can't improve hole cleaning efficiency by optimizing the drilling fluid's rheological properties. Due to low cuttings carrying energy of gas in horizontal gas drilling, large cuttings not only can't be circulated out of down hole in time but also can't be reground by the bit teeth as in vertical gas drilling do (Chen et al., 2014). As a result, they are easily accumulated in the horizontal wellbores, which may lead to the accidents such as wellbore plugging and pipe sticking.

In order to solve the problem, the field-applied gas flow rate in horizontal gas drilling is much higher than that in vertical gas drilling for hole cleaning (Guo et al., 1994; Chen et al., 2014). However, high gas flow rate has several detrimental effects on drilling operations including near-bit borehole washout, near-bit borehole collapse, pipe and casing erosion, and ice-balling of drill bit (Guo and Liu, 2011). Therefore, it is highly desirable to develop new technologies to eliminate cuttings accumulation meanwhile reduce the gas flow rate required for hole cleaning in horizontal gas drilling.

According to the field experience, drill cuttings returned to surface in gas drilling are dust-like with equivalent average diameter between 0.08 mm and 0.1 mm. If the cuttings size can be reduced at bottom hole by certain means, cuttings accumulation in the horizontal wellbores will be eliminated, meanwhile the gas flow rate required to clean the hole can also be lowered. This gave

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http://dx.doi.org/10.1016/j.jngse.2015.12.033
1875-5100/

us an idea of crushing the cuttings right after they are generated so that cuttings accumulation in horizontal gas drilling is eliminated (Chen et al., 2015). The idea motivated our development of JMB on the basis of jet comminution technique in this study. In order to promote the optimal design and execution of the JMB, analytical models were developed for predicting the required cutting's impact velocity and designing the minimum length of accelerating tube in JMB, meanwhile the factors affecting the optimal design of JMB were also investigated.

2. Jet mill bit

A new type of bit called jet mill bit (JMB) has been designed and manufactured in this research. Its sketch and flow diagram are shown in Fig. 1. In principle the JMB is different from conventional PDC bit in that it is constructed with jet comminution device that use high velocity gas jet to impart energy to cuttings to project against comminution targets for cuttings size reduction. It is understood that the JMB has no junk slots or flow by that conventional drill bits have around the bit to allow drilling fluid and cuttings to flow through annulus between the bit and the wellbore. The cuttings are circulated out through the cuttings-suction channel inside the bit instead of the annulus. In horizontal gas drilling with a JMB, drill cuttings in the bottom hole are affected into a highly turbulent flow by asymmetric high-velocity jet from the cuttings agitation and cleaning nozzle, and then they are sucked into the throats under the suction of backward jet nozzles and the lift of bottom hole flow. Drill cuttings from the bottom hole are accelerated in the accelerating tubes. At the end of the accelerating tubes, the high velocity cuttings are crushed to the comminution targets. As a result of the jet comminution process large cuttings become small particles.

The concept of jet comminution is not new. It uses high velocity gas jet to impart energy to particles to project against a fixed target for size reduction in other industries to produce powders. The carrier fluid is usually compressed air and nitrogen (Chamayou and Dodds, 2007; Mohammad et al., 2012). The particles-size reduction occurs by impact, dissociation of fluid wedge effect, collision or shearing by particles—particles or particles-wall interactions, which can produce particles in sizes in dust scale (Muller et al., 1995; Fisher, 2006). In the JMB, high velocity gas is an accelerating carrier. Its drag force accelerates cuttings to obtain high velocity. A high-level impact stress is created when the high-velocity cuttings are bumped to the comminution targets. During this process, impact stress will lead to the micro-cracked cuttings crushing (Cui et al., 2006). The impact stress can be estimated as (Liu and Sun, 2005)

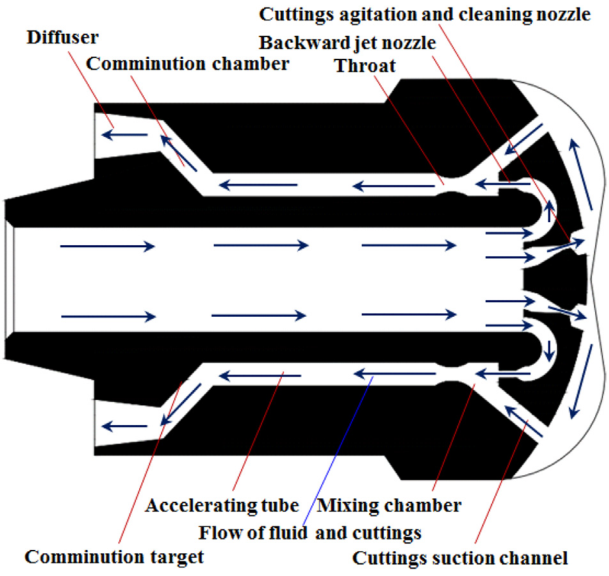

Fig. 1. Sketch and flow diagram of jet mill bit.

$$p = \rho_s \cdot c \cdot v_i \tag{1}$$

As shown in the above equation, cutting's impact velocity is the key parameter of jet comminution, while it is mainly determined by the length of accelerating tube for a given gas velocity at the outlet of backward jet nozzle of JMB. Therefore, required cutting's impact velocity and minimum length of accelerating tube in JMB can be designed to support the design and execution of JMB in horizontal gas drilling.

3. Mathematical model

3.1. Required cutting's impact velocity

We propose the following model to determine the required cutting's impact velocity (derivation is given in Appendix A)

$$v_{ri} = \sqrt{7.94 \times 10^3 \cdot f_i \cdot W_i \cdot \left(\frac{10}{\sqrt{d_{80}}} - \frac{10}{\sqrt{D_{80}}} \right)} \tag{2}$$

where f_i is the fraction of cutting's crushing and comminuting energy from impacting on the comminution target of JMB (dimensionless); W_i is Bond work index for crushing and comminuting, it is defined as the work input in kWh/short ton (1 short ton = 907 kg) that is required to reduce the particle from an infinitely large particle size to 80% passing 100μm, Table 1 shows the Bond work index for crushing and comminuting cuttings of different lithology.

3.2. Minimum length of accelerating tube in JMB

Based on the required cutting's impact velocity, minimum length of accelerating tube in JMB can also be designed. It can be estimated as (derivation is given in Appendix B)

$$\begin{cases} l_m = \dfrac{v_0 v_a}{g}\left(\ln \dfrac{v_a}{v_a - v_{ri}} - \dfrac{v_{ri}}{v_a}\right) & (\mathrm{Re} < 1) \\ l_m = \dfrac{2v_0^{1.5}}{g}\left(\dfrac{2v_a - v_{ri}}{\sqrt{v_a - v_{ri}}} - 2\sqrt{v_a}\right) & (1 \le \mathrm{Re} \le 500) \\ l_m = \dfrac{v_0^2}{g}\left(\dfrac{v_{ri}}{v_a - v_{ri}} + \ln \dfrac{v_a - v_{ri}}{v_a}\right) & (500 \le \mathrm{Re} \le 2 \times 10^5) \end{cases} \tag{3}$$

Where (Gray, 1958; Guo and Liu, 2011)

Table 1
Bond work index for crushing and comminuting cuttings of different lithology in drilling (Bond, 1961; Zheng, 1999).

Lithology	Density	Bond work index for crushing and grinding
	g/cm^3	kWh/short ton
Clay	2.23	7.10
Sandstone	2.68	11.53
Limestone	2.69	11.61
Oil shale	1.76	18.10
Shale	2.58	16.40