Journal of Petroleum Science and Engineering 168 (2018) 217–225

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Development of a mathematical model and experimental validation of borehole instability due to gravity displacement during drilling in a fractured formation

Dong Xiao[a,b,*], Yingfeng Meng[a,b], Gao Li[a,b], Gang Shu[c], Shutao Li[a,b], Yuying Guo[a]

[a] College of Petroleum and Natural Gas Engineering, Southwest Petroleum University, Chengdu, China
[b] State Key Lab of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, China
[c] Engineering Technology Research Institute of PetroChina Southwest Oil & Gas Field Company, Chengdu, China

ARTICLE INFO

Keywords:
Gravity displacement
Fracture formation
Drilling
Mathematical model
Model experiment

ABSTRACT

Lost Circulation and overflow often occur concurrently in fracture formation due to gravity displacement, causing a downhole complexity, out of control for blowout, reservoir damage, well control difficulty, drilling cycle prolonging and cost overrun. There is still ongoing investigation and lack of basic theoretical understanding. In this paper, a mathematical model of gas-liquid gravity displacement is established and solved, as well as verified by model experiment. The results are used to develop a theoretical foundation that explains the phenomena, and a solution method is proposed for practical application.

1. Introduction

During drilling through a single fracture in a fractured formation, lost circulation and overflow often occurr concurrently due to the complex formation fracture network. (Wang et al., 2012; Lee, 2015). This leads to 1) abnormally high total well hydrocarbon gas after drilling (Lu et al., 2017), 2) the difficulty of killing well after gas cutting due to the rapid transport of gas (Akimov et al., 2010), 3) severe lost circulation [Xu et al., 2016], and 4) low drilling efficiency and high operation risk (Wang and Sheng, 2015). Previous studies (Shu et al., 2011; Jia et al., 2012; Zhang et al., 2014) showed that gravity displacement caused by the difference in density of formation fluid and drilling fluid is the main cause of these consequences. In order to solve this problem, published literature indicate the following four measures: 1) holistic approach and empirical formula, 2) engineering measures and solution procedures, 3) development of lost circulation model and 4) plugging mechanism and the application of plugging materials (Zeng et al., 2005; Hauge et al., 2013; Liang et al., 2014; Eric Cayeux and Benoit Daireaux, 2016; Li et al., 2017). However, these measures lack basic theoretical research and model description, and do not address the problem of gravity displacement.

The process of gravity displacement involves two complex coupling processes. First, there is a strong fluid-structure coupling between formation fluids and formation fractures. Second, there is also a dynamic coupling between formation fluid and wellbore fluid. Therefore, the law of gravity displacement must be based on the above two coupling processes. Only in this way can we form a comprehensive understanding and analysis and provide a theoretical basis for the prevention and control of gravity replacement. Based on the above factors, a mathematical model of gas-liquid gravity displacement is proposed and verified by model experiment in this paper.

This paper is organized as follows. Section 2 is investigated the causes and conditions of gravity displacement. The mechanism of flow field characters are revealed. Section 3 is established governing equation of gravity displacement and formed computational method combining with boundary conditions and secondary equation. Section 4 is designed with an experimental device based on real fracture, carried out the model experiment, tested and validated the mathematical model. Calculating results match up with experimental results and lost circulation and overflow rate can be calculated with interrelated formation parameters. The research results provide a theoretical foundation for seeking a solution method, explaining its phenomenon and practical treating.

2. Causes and conditions of gravity displacement

At present, there is no unified understanding of the mechanism of gravity displacement and the lack of interpretation of the phenomenon. When a gravity displacement occurs on site, it is usually treated as a single lost circulation (Zhang et al., 2012) or a single overflow (Meng

* Corresponding author. Southwest Petroleum University, No.8 Xindu avenue, Chengdu, China.
E-mail address: swpuxiaodong@126.com (D. Xiao).

https://doi.org/10.1016/j.petrol.2018.05.030
Received 16 March 2018; Received in revised form 8 May 2018; Accepted 9 May 2018
Available online 25 May 2018
0920-4105/

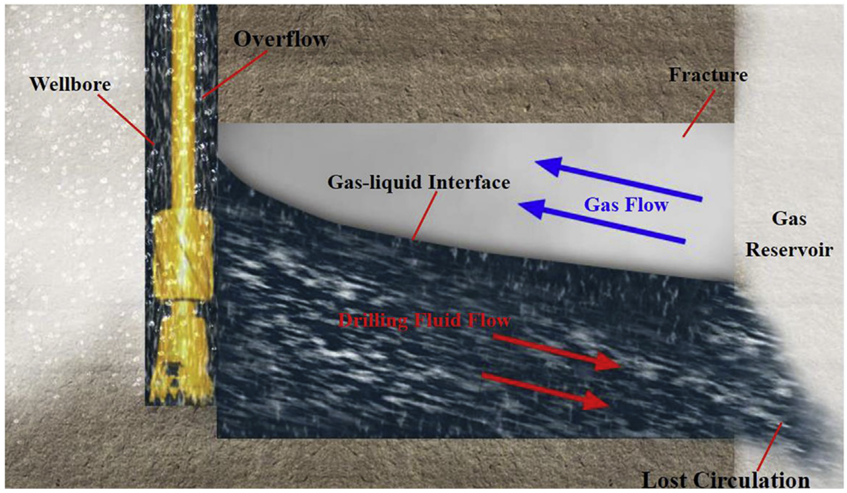

Fig. 1. Schematic diagram of gravity displacement.

et al., 2015; Li et al., 2016). Based on the relationship between wellbore pressure and formation pressure and gas-liquid two-phase flow characteristics, the causes and conditions of gravity displacement of fractured formation are analyzed as follows.

2.1. Conditions

Fig. 1 is a schematic diagram of coexistence of lost circulation and overflow due to gravity displacement. It occurring should possess three conditions: 1) the formation has a fracture path that allows drilling fluid to flow from the wellbore into the formation, 2) when there is a large amount of drilling fluid leakage, there is enough space in the formation to accommodate, 3) the wellbore pressure is in the gravity displacement window. The first two conditions are relatively easy to understand, so the following is mainly analyzed for the third condition.

Seen from Fig. 2, the area ABDO represents the fracture surface. According to the pressure balance relationship between wellbore and formation, the following relation is shown.

The condition of just lost circulation and not overflow:

$$P_A > P_B - \Delta P_{up} - \rho_m g|AE| \tag{1}$$

The condition of just overflow and not lost circulation:

$$P_A < P_B + \Delta P_{down} - \rho_m g|AO| \tag{2}$$

The condition of overflow and lost circulation occurring concurrently:

$$P_B + \Delta P_{down} - \rho_m g|AO| < P_A < P_B - \Delta P_{up} - \rho_m g|AE| \tag{3}$$

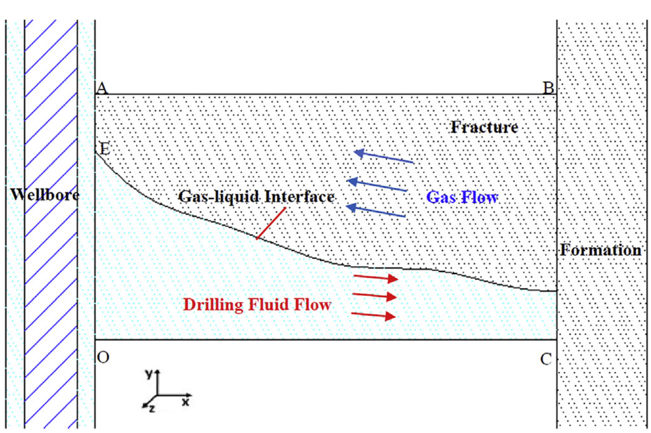

Fig. 2. Gravity displacement geometric model.

In those equations above, P_A is the wellbore pressure corresponding to the top of the fracture, Pa; P_B is the internal pressure of the gas layer near the wellbore, Pa; ΔP_{up} and ΔP_{down} are respectively the gas flow pressure loss on the upper part of the fracture and the flow pressure loss of the lower part of the drilling fluid, Pa ; ρ_m is the density of the drilling fluid, kg/m^3.

Equation (3) reflects the gravity displacement narrow window. The reason for the gravity displacement window is that the density of the gas in the formation is less than the density of the drilling fluid, so that the vertical pressure gradient in the gas layer is less than the vertical pressure gradient of the corresponding drilling fluid. And it changes the pressure balance between the wellbore and the formation. Therefore, when the fracture is obviously extended in the vertical direction, such as the high and steep fracture, it is easier to lead to overflow-lost circulation coexistence.

From the above analysis, if the wellbore pressure is obviously greater than that of the formation pressure (for example, greater than 1 MPa), lost circulation occurs. If the wellbore pressure is obviously less than that of the formation pressure (for example, less than 1 MPa), overflow occurs. Only when the wellbore pressure is close to the formation pressure (for example, the difference between the two is less than 0.1Mpa), overflow-lost circulation coexistence occurs. The formation pressure is distinct from the radial distance of the borehole after drilling. Therefore, to be accurate, the above mentioned “formation pressure” refers to the “pressure in the adjacent hole fracture".

2.2. Causes

Actual drilling engineering, regardless of the use of conventional overbalance drilling or under-balanced drilling, wellbore pressure and formation pressure difference are generally not stable in a range of 0.1 MPa. If from this angle to analyze, overflow -lost circulation coexistence by gravity displacement would be hard to occur. However, the key factor determining whether the gravity displacement occurs is whether the pressure in the wellbore is close enough to the pressure in the adjacent hole fracture. Under certain conditions, these two pressures are easier to meet the conditions of “proximity”. The following is discussed in four aspects: 1)produced gas in the formation will lead to pressure drop funnel, 2) drilling fluids crowd out formation gas, 3)shut-in after the overflow, and 4)wellbore pressure fluctuation.