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Research Article

Migration laws of natural gas hydrate solid particles with different abundance in horizontal wells☆,☆☆

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Abstract

When a horizontal well is drilled through the natural gas hydrate (NGH) strata with different abundance, the NGH-bearing solid debris tends to lead to the deposit and adhesion of solid particles in the lateral sections and consequently cuttings carrying is not smooth. In this paper, the critical return rate model of drilling fluid in the case of cuttings rolling (normal drilling) and saltation (pump off for sand settling) under NGH adhesion in the laterals was established according to the force and migration laws of cuttings under the condition of multiphase flow in a horizontal well and the particle migration theory. Then, numerical simulation was conducted and the influential factors and migration laws of cuttings starting in the case of normal drilling and pump off were analyzed. And the following results were obtained. First, the critical starting flow rate decreases with the rise of NGH abundance and it is higher when the NGH adhesion is taken into account. Besides, the higher the NGH abundance, the greater the effect of NGH adhesion. Second, the critical starting flow rate increases with the rise of drilling cuttings particle size when the NGH abundance is less than 85%; and it decreases with the rise of drilling cuttings particle size when the NGH abundance is more than 85%. Third, the critical starting flow rate decreases with the rise of drilling fluid density and viscosity. And fourth, under the same conditions, the critical return rate for saltation is about 1.28 times that for rolling. It is suggested that the rolling model should be adopted for the normal drilling while the saltation model for the recycle after pump-off sand settling. The research results are of great significance to the optimization of NGH drilling parameters and the reduction of drilling safety risks.

Keywords: Different abundance; Natural gas hydrate layer; Horizontal well; Solid cuttings; Migration law; Cuttings carrying laws; Critical flow rate; Numerical simulation; Flow field analysis

During the horizontal drilling in natural gas hydrate (HGH or hydrate) layers, the hydrate particles and the cuttings flow together with the drilling fluid in lateral sections. Due to the minimal changes of temperature and pressure in lateral sections, the hydrate particle decomposition is small [1]. The increase in drag and torque of drill string due to poor wellbore cleanup could severely restrict the horizontal well extension capacity [2,3]. The complex multiphase flow of liquids and solids, especially the solid phase migration behavior, is the core of cutting migration in the lateral section of a horizontal well.

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1. Models of hydrate solid particle migration in lateral sections

During horizontal drilling in NGH layers with different abundance, hydrate particles and the cuttings flow together with drilling fluid in the lateral sections (Fig. 1). Due to the minimal changes of temperature and pressure in the lateral sections, the hydrate particle decomposition is small. The density of cuttings from NGH layers is lower than that of conventional cuttings (generally 1140–2330 kg/m^3 under the abundance of 10–80%). Hydrate particles and cuttings have a strong adhesion force, making it prone to solid-phase deposition and adhesion and coalescence in lateral sections. The migration behavior of hydrate cuttings in lateral sections is different from that in vertical sections. The safe and effective migration of hydrate cuttings is mainly challenged by (1) the cutting migration behavior different from that under disturbance of drillpipe during horizontal drilling; and (2) the higher cohesion among the particles in hydrate cuttings beds as compared with failure conditions of the cuttings beds during horizontal drilling. The models of solid particle migration in lateral sections are introduced as follows.

1.1. Force model of hydrate particles

The destruction of hydrate cuttings beds formed in lateral sections is mainly determined by the critical start-up of the cuttings on their surface. The critical start-up refers to the critical state of the cuttings on the cuttings bed surface from idle to motion. In terms of mechanics, it is mainly sensitive to its own properties and the forces on the cuttings. Forces on cuttings include gravity, buoyancy, flow drag force, pressure gradient force, flow lifting force, interparticle cohesion force, Bassett force, additional mass force and Magnus effect force [4,5]. Force analysis of cuttings is shown in Fig. 2.

The forces on hydrate cuttings are analyzed separately.

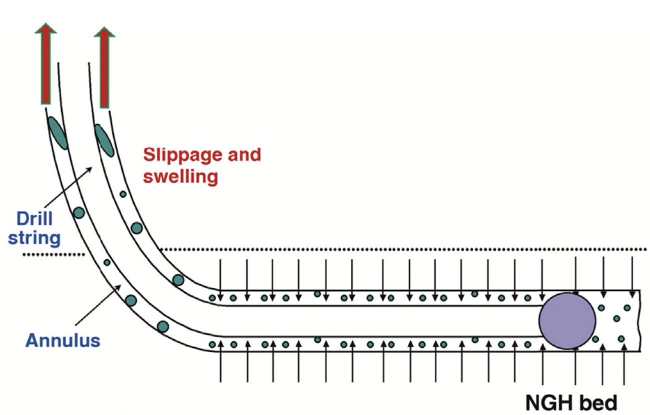

Fig. 1. Schematic diagram of flow in wellbore encountering a marine NGH layer.

1.1.1. Gravity (G)

$$G = \rho_s g \frac{\pi d_s^3}{6} \tag{1}$$

where, G is the gravity on hydrate cuttings, N; similarly, ρ_s: the mixing density of hydrate cuttings, kg/m^3; d_s: the diameter of hydrate cuttings, m; g: the gravity acceleration, m/s^2.

The mixing density of hydrate cuttings is determined by:

$$\rho_s = \rho_H x + \rho_c (1 - x) \tag{2}$$

where, ρ_H is the hydrate density, kg/m^3; similarly, ρ_c: the density of the silt in hydrate cuttings, kg/m^3; x: the hydrate abundance in hydrate cuttings, dimensionless.

1.1.2. Buoyancy (F_B)

$$F_B = \rho_l g \frac{\pi d_s^3}{6} \tag{3}$$

where, F_B is the buoyancy on hydrate cuttings, N; ρ_l is the drilling fluid density, kg/m^3.

1.1.3. Flow drag force (F_D)

The joint action of friction and shape resistance caused by drilling fluid flowing through the surface of hydrate cuttings is the flow drag force. The direction is along the flow direction of the drilling fluid. The flow drag force is mainly generated by the drilling fluid velocity and viscosity, with the expression [6,7] as:

$$F_D = C_D \frac{\pi \rho_l (v_l + v_s)(v_l - v_s) d_s^2}{8} \tag{4}$$

where, F_D is the flow drag force on hydrate cuttings, N; similarly, v_l: the drilling fluid velocity, m/s; v_s: the solid hydrate cutting velocity, m/s; C_D: the drag coefficient, dimensionless.

1.1.4. Pressure gradient force (F_P)

The direction of the pressure gradient force is along the flow direction of the drilling fluid. The force is generated by the pressure gradient of drilling fluid in wellbores. It is expressed as [8]:

$$F_P = \frac{\pi d_s^3}{6} F_{dp} \tag{5}$$

where, F_P is the pressure gradient force, N; F_{dp} is the pressure gradient, Pa/m.

1.1.5. Saffman lifting force (F_L)

The flow rate through the top of hydrate cuttings beds is the wellbore flow rate, while the flow rate through the bottom of hydrate cuttings beds is the interparticle permeated water flow rate, which is much less than the flow rate at the top. According to the Bernoulli's equation, the flow rate difference produces a pressure gradient difference acting on hydrate