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Research Article

Dynamic analysis of a liquid droplet and optimization of helical angles for vortex drainage gas recovery☆

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Abstract

Downhole vortex drainage gas recovery is a new gas production technology. So far, however, the forces and motions of liquid phase in the swirling flow field of wellbores during its field application have not been figured out. In this paper, the forces of liquid droplets in the swirling flow field of wellbores were analyzed on the basis of two-phase fluid dynamics theories. Then, the motion equations of fluid droplets along axial and radical directions were established. Magnitude comparison was performed on several typical acting forces, including Basset force, virtual mass force, Magnus force, Saffman force and Stokes force. Besides, the formula for calculating the optimal helical angle of vortex tools was established according to the principle that the vertical resultant force on fluid droplets should be the maximum. And afterwards, each acting force was comprehensively analyzed in terms of its origin, characteristics and direction based on the established force analysis model. Magnitude comparison indicates that the forces with less effect can be neglected, including virtual mass force, Basset force and convection volume force. Moreover, the vertically upward centrifugal force component occurs on the fluid droplets in swirling flow field instead of those in the conventional flow field of wellbores, which is favorable for the fluid droplets to move upward. The reliability of optimal helical angle calculation formula was verified by means of case analysis. It is demonstrated that with the decrease of well depth, the fluid-carrying capability of gas and the optimal helical angle increase. The research results in this paper have a guiding significance to the optimization design of downhole vortex tools and the field application of downhole vortex drainage gas recovery technology.

Keywords: Gas well; Vortex tool; Drainage gas recovery; Swirling flow field; Force analysis; Magnitude comparison; Helical angle; Optimization

1. Overview of downhole vortex drainage gas recovery

Downhole vortex drainage gas recovery is a new gas production technology [1,2]. It is one of the innovative technology projects on low-productivity wells of the Stripper Well Consortium (SWC) sponsored by the United States Department of Energy (DOE) since 2002 [3]. PetroChina adopted this technology in 2011 and promoted it in domestic operations [4].

Here, the mechanism of downhole vortex drainage is described. When gas/liquid mixture enters the downhole vortex tool, the mixture starts to rotate and flow upward in the tubing along helical routes (Fig. 1). Due to the differences in densities, gas and liquid are partially separated during the course. Liquid is thrown onto the wall of the tubing, while a gas core with upward flow in rotation is formed in the center of the tubing, and hydrostatic pressure on gas reduces. At the same time, the rotation provides the flow with a horizontal component, which can drive and maintain the vortex flow in the tubing [5]. Vortex drainage can effectively reduce frictional losses and slippage losses in the tubing, so as to reduce

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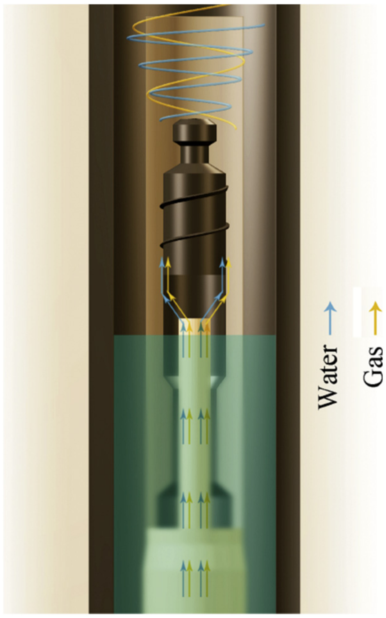

Fig. 1. Diagram of vortex drainage.

overall pressure drop. In addition, vortex drainage can effectively reduce the critical fluid-carrying flow rate and prevent wax from depositing on sidewalls [6].

Some scholars abroad performed simulation tests in labs [5,7] to verify the effectiveness of vortex drainage. They also made CFD numerical simulations [8–11] to highlight the impacts of production parameters and tool structures on the performance of vortex drainage. Currently, however, studies seldom deal with the theories in the swirling flow field of wellbores, and there are no mathematical models for forces on and flow patterns of fluids in wellbores. In this study, forces on liquid droplets in the swirling flow field of wellbores were analyzed according to the two-phase fluid dynamics theories, and the optimal helical angle for vortex tools was determined depending on the properties of vertical forces on such liquid droplets.

2. Dynamic analysis of liquid droplets in wellbore

During downhole vortex drainage gas recovery, liquid droplets in wellbores present vortex flow. Also known as swirling flow, vortex flow involves both rotation velocity and linear velocity [8].

Forces on liquid droplets in the swirling flow fields of wellbores are significantly different from those in the conventional flow fields of wellbores. In conventional flow fields, liquid droplets are subject to gravity, buoyancy and gas drag forces only [9], whereas forces on liquid droplets in the swirling flow fields are much complicated. Forces on spherical liquid droplets can be classified into three categories [10]: ① forces irrelevant to the relative motions of gas–liquid droplets, including gravity, buoyancy, centrifugal force and radial pressure gradient force; ② vertical forces determined by the relative motions of gas–liquid droplets and along the directions of such relative motions, including gas drag force, virtual mass force, Basset force and convection volume force; and ③ lateral forces determined by the relative motions of gas–liquid droplets and vertical to the directions of such relative motions, including Magnus force and Saffman force.

2.1. Force analysis of liquid droplets

2.1.1. Forces irrelevant to relative motions

2.1.1.1. Gravity. Gravity (F_G) of a spherical liquid droplet can be expressed as follows:

$$F_G = \frac{\pi}{6} d_p^3 \rho_l g \tag{1}$$

2.1.1.2. Buoyancy. Buoyancy (F_b) of a spherical liquid droplet can be expressed as follows:

$$F_b = \frac{\pi}{6} d_p^3 \rho_g g \tag{2}$$

2.1.1.3. Centrifugal force. Centrifugal force (F_c) of a liquid droplet in the swirling flow field under tangential velocity can be expressed as follows:

$$F_c = \frac{\pi}{6} d_p^3 \rho_l \frac{v_\theta^2}{r} \tag{3}$$

The angle between the upward centrifugal force away from the axis and the horizontal direction is the tool's helical angle θ_h [5].

2.1.1.4. Radial pressure gradient force. Radial pressure gradients of the swirling flow field may induce an uneven distribution of pressures in surrounding areas, and eventually generate radial pressure gradient force (F_p) on liquid droplets [11]:

$$F_p = \frac{\pi}{6} d_p^3 \rho_g \frac{v_\theta^2}{r} \tag{4}$$

The direction of radial pressure gradient force is opposite to the direction of pressure gradient.

2.1.2. Vertical forces

2.1.2.1. Das drag force. During the movement of liquid droplets in viscous gases, viscous surfaces on liquid droplets may induce drag (F_d) [12], which can be expressed as follows:

$$F_d = \frac{1}{8} \pi C_D d_p^2 \rho_g |v_g - v_l| (v_g - v_l) \tag{5}$$

The direction of gas drag force is opposite to the direction of relative motions of liquid droplets in the gas. Calculation of drag factors may involve complicated processes. Different