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Particle image velocimetry analysis of plane flow field induced by drill string planetary motion based on superposition principle

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ABSTRACT

To study the law of a fluid plane flow induced by the planetary motion of the drill string and solve the practical engineering problems, such as improving the cutting-carrying capacity of a drilling fluid and reducing the flow pressure loss or damage to the drill string by whirling, a method based on the superposition principle is proposed. The flow field induced by the planetary motion is decomposed into a centrifugal force field through an equal angle rotation of the drill string and wellbore, and a flow field induced by through the simultaneous rotation of the drill string and wellbore. To analyze the latter, an experimental device was designed to measure the plane flow field of a fluid induced by the rotation of the internal rod and outer cylinder, and a particle image velocimetry experiment was performed. The results are as follows: the velocity of the plane flow field induced by the rotation of the internal rod and outer cylinder has an approximately symmetrical distribution, with the line connecting the cross section centers of the outer cylinder and inner rod as the axis of symmetry; when the outer cylinder is motionless and the inner rod rotates eccentrically, there is a critical value of the eccentricity upon which the secondary flow occurs and it is 0.7, moreover, the secondary flow occurs in a place far away from the inner rod and near the wall of the outer cylinder; when the inner rod and outer cylinder rotate in the same direction, the occurrence of the secondary flow is related to the eccentricity, and the area of distribution of the secondary flow expands with the increase in the eccentricity, for example, when the inner rod and outer cylinder rotate in the same direction with the speed of 60 r/min and 120 r/min respectively, the secondary flow occurs only when the eccentricity exceeds 0.4, and the area of the secondary flow becomes larger and larger with the increase of the eccentricity; when the inner rod and outer cylinder rotate in the same direction, the occurrence of the secondary flow is related to the difference in rotation speed between the inner rod and outer cylinder, and the area of distribution of the secondary flow expands with the increase in this difference, for example, when the eccentricity is 0.4, the secondary flow disappears or does not occur on the rotating speed difference being 0, and the area of distribution of the secondary flow expands with the rotating speed difference increasing from 60 r/min to 120r/min; when the inner rod and outer cylinder rotate in opposite directions, for example, when both of them rotate at speed of 60 r/min and the eccentricity of 0.2, the secondary flow occurs, the distribution of the secondary flow is approximately symmetrical and shaped like a crescent moon, and the area of distribution expands with the increase in the rotation speed of the inner rod or outer cylinder and the increase in eccentricity.

1. Introduction

During an oil drilling process, the compression rotating drill string not only rotates, but also the whirling will occur (Li, 2013; Gao et al., 1996; Qu and Xu, 1997; Li et al., 2008; Zhang et al., 2013), i.e., revolution. Such complex motion of the drill string is also known as planetary motion (Cui et al., 2005, 2007; Zhang et al., 2010). The flow of drilling fluid in an annular space formed by a wellbore and the drill string is not only an axial flow, but also a plane flow (Li et al., 1995; Wang, 2015; Quan, 2015) induced by the planetary motion of the drill string, and the axial flow and plane flow becomed superposed, forming a complex eccentric spiral flow. The law of the spiral flow of a drilling fluid has been the focus of studies in the field of petroleum engineering. However, because of the complexity of the flow, few analytical solutions have been derived, and most studies have been based on a numerical solution and particle image velocimetry method, of which, an analytical solution to the flow of Newtonian fluids in an annular space for the planetary motion in an inner cylinder, as given by Cui et al. (Cui

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and Ji, 1996) is representative. Because the expression form is too complex, its practical application is limited. Although many numerical simulation methods (Ballal and Rivlin, 1976; Kazakia and Rivlin, 1977; Oney et al., 2015; Pang et al., 2015; Yang et al., 2017), the accuracy of the results cannot be evaluated. The particle image velocimetry (PIV) method not only can display the physical form of a fluid flow field and the flow itself, it can also provide quantitative information on an instantaneous full field flow, which is increasingly in wide use; however, because of its special requirements, PIV experimental studies of an eccentric spiral flow have mainly focused on axial flows (Zhou, 2006; Wang et al., 2011, 2012; Xi et al., 2017), and there has yet to be a PIV experiment conducted on a plane flow field induced by the planetary motion of a rod string. However, an analysis of the laws of the fluid plane flow induced by planetary motion of the drill string is of great practical significance for a velocity distribution, secondary flow distribution, cutting-carrying capacity of the drilling fluid, flow pressure loss, and drill string whirling rule. For this reason, in this paper, the physical model of a fluid plane flow induced by planetary motion of the drill string is decomposed taking a Newtonian fluid as an example based on the superposition principle, and the two flow fields are analysed respectively to provide new ideas for deriving analytical solutions. At the same time, a PIV experiment is carried out. The experimental analysis results and experimental data can provide some support for the selection of a numerical simulation method and an evaluation of the simulation results, thereby providing some help to the study of eccentric spiral flow of a drilling fluid.

2. Solution ideas

The Navier-Stokes equation has been used for studies on incompressible Newtonian fluid dynamics; however, this equation is only applicable to the inertial coordinate system. However, it is more convenient to discuss the plane flow field of a fluid induced by planetary motion of the drill string in a non-inertial coordinate system, and therefore, a bipolar coordinate system was established by Cui et al.(Cui and Ji, 1996). The consequent problem is that the transformation from an inertial coordinate system to a non-inertial coordinate system makes the equation more complex and the solution more complicated, which is also the main reason for the limited application of their research results. The fluid in this paper is an incompressible Newtonian fluid: (1) the viscosity is constant; (2) the density is constant; (3) no gasification; (4) the shear stress is proportional to the velocity gradient. Under these conditions, the principle of superposition is valid. This paper first decomposes the physical model of the planetary motion of the drill string, as shown in Fig. 1.

As indicated in the figure above, the planetary motion of the drill string can be seen as the superposition of two motions. The first motion is the rotation of the wellbore at angular velocity Ω with the drill string revolving around the axis of the wellbore at the same angular velocity Ω; this flow field is a centrifugal force field. After stabilizing, the particles of each fluid have the same angular velocity. The tangential velocity of each particle is $u = \Omega r$, where r is the distance between the fluid particle and the center of the cross section of the outer cylinder.

The second motion is the rotation of the wellbore at angular velocity Ω with the drill string rotating on its own axis at an angular velocity of ω-Ω, and there have yet to be any related studies on what the flow field is under this motion. Owing to the simultaneous rotation of the drill string and the wellbore, the plane flow field of an eccentric annulus is formed. It is easy to establish an inertial coordinate system to achieve a solution, which is convenient for the development of a PIV experiment. This paper focuses on a PIV experimental analysis of this type of flow field.

3. Experimental device, method, and conditions

3.1. Experimental device

An experimental device for measuring the plane flow field of a fluid induced by the rotation of the inner rod and outer cylinder was designed, and a patent for the invention (Li et al., 2017), shown in Fig. 2 (a), is under application.

The experimental device consists of the main body, inner rod rotation device, outer cylinder rotation device, PIV measurement device, and other elements. The main body of the experimental device is a tetragonal prism frame structure formed by welding the top plate and the middle plate on four columns with three parallel and equidistant deviation adjustment holes on the top plate. By adjusting the position of the three bolts under the reducer(1) that controls the self rotation of the inner rod, the eccentricity of the internal rod (that is, the simulated drill string) is adjusted. The inner rod rotation device is composed of the AC motor(1), reducer(1), drive rod, polishing rod, plexiglass rod, etc. The upper end of the polishing rod is linked with the drive rod on the reducer(1) through a coupling. The lower end of the polishing rod is concentrically connected to the plexiglass rod through screw threads to constitute the inner rod (that is, the simulated drill string). The AC motor(1) controller controls the rotating speed and rotation direction of the inner rod. The outer cylinder rotation device is composed of the AC motor(2), reducer(2), drive shaft, synchronous wheel, synchronous belt, outer cylinder, insert bearing with seat, etc. The outer cylinder is a plexiglass tube (that is, the simulated wellbore), which is fixed by two set screws inside the insert bearing with seat. Two insert bearings with seat is fixed on the top plate and the middle plate by bolts respectively. At the same time, two insert bearings with seat are equivalent to alignment bearings to ensure the wellbore to be vertical and reduce lateral sway. One synchronous wheel is fixed to the outer of the plexiglass tube with four set screws, and the synchronous belt is intertwined between the two synchronous wheels to form a synchronous belt drive mechanism. Another synchronous wheel is connected to the drive shaft on the reducer(2) under an interference fit. The lower end of the drive shaft is equipped with a supporting table and keyway, which passes through and is supported on the rotation reducer(2) of the outer cylinder and the AC motor(2) controller controls the rotating speed and

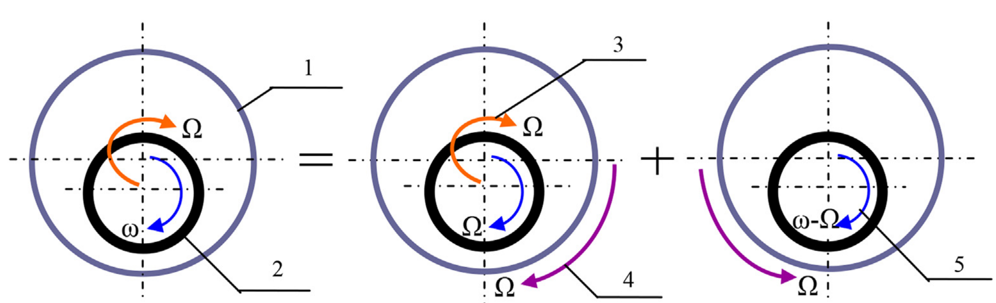

Fig. 1. Decomposition of physical model of planetary motion of the drill string.
1- wellbore 2- drill string 3- whirl of the drill string 4- rotation of the wellbore 5- rotation of the drill string.