Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2008,20(1):67-73
sdlj.chinajournal.net.cn

# A THREE-SEGMENT HYDRAULIC MODEL FOR ANNULAR CUTTINGS TRANSPORT WITH FOAM IN HORIZONTAL DRILLING*

CHENG Rong-chao, WANG Rui-he
College of Petroleum Engineering, China University of Petroleum(East China), Dongying 257061, China,
E-mail: chlongch_1117@163.com

(Received April 16, 2007, Revised August 9, 2007)

**Abstract:** Through mechanical analysis, an improved hydraulic model for annular cuttings transport with foam was established for horizontal drilling. Based on the two critical inclination angles, the entire well was divided into three segments. The Bagnold stress, generalized power law rheological model and modified hindered particle settling velocity in foam fluid were adopted in the model to improve the simulation accuracy. The proposed model allows more precise prediction of cuttings transport property in the whole range of well inclination angle. Model performance was examined via case study and experimental data. Simulation results given by the propulsion iteration and trial-and-error method agree well with in-situ horizontal well drilling practice for the case study, and the comparison between the model prediction and Capo's experimental data shows satisfactory agreement.

**Key words:** horizontal well, foam fluid, drilled cuttings, hydraulic model, well inclination angle

## 1. Introduction

In the interest of lower exploratory development cost and higher oil recovery ratio in current petroleum industry, the underbalanced horizontal drilling (UBD) technology has been developing as one of the highlights in international petroleum drilling market. As a special form of UBD, foamed drilling shows pronounced advantages in the improvement of hole cleaning efficiency, hydrocarbon reservoir acquisition and protection, increase in penetration rate and reduction in drilling cost. Hence, it has been extensively applied throughout the world. The cuttings transport performance with foam drilling fluid, however, has been less described because of the complexity of multiphase flow. Most of present related publications slight the difference of cuttings transport at different inclination angles when over-pursuing relatively simplified models adoptable for much longer well section. For instance, the two-layer mechanical models established by Martins[1], Doan[2] and Li[3] cannot describe the cuttings transport property at relatively higher inclination angles when moving bed and stationary bed exist simultaneously, and the three-layer mechanical models presented by Nguyen[4], Cho[5] and Ozbayoglu[6] cannot simulate the Boycott phenomenon at intermediate inclination angles. To our knowledge, domestic researchers mostly laid their emphasis on the mechanisms and experiments of two-phase flow[7-9], and much less is known about the three-phase flow property in concentric and eccentric annuli.

In correspondence with the horizontal drilling practice, this article proposes an improved cuttings transport theoretical model with foam fluid for horizontal drilling. Model equations and related algorithm are presented. Meanwhile, a case study and comparison with experimental data are conducted to verify its rationality and accuracy.

* Project supported by the National High Technology Research and Development Program of China (863 Program, Grant No. 2006AA06Z218), the National Natural Science Foundation of China (Grant No. 50574062).

**Biography:** CHENG Rong-chao (1980-), Male, Ph. D. Student

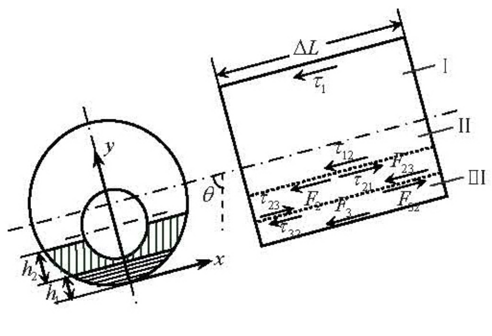
## 2. Model building

In the highly deviated wellbore, the radial components of both gravity and slip velocity of solid particles increase with the augment of inclination angle, so does the tendency of particles to deposit towards the low side of annulus. As the inclination angle increases to the first critical angle $\theta_{c1}$ from vertical, the radial force on the particle enables it to depart from the main mud stream, entrap itself into the lower annulus and slide in the reverse direction of the annular return velocity. As the inclination angle reaches the second critical angle $\theta_{c2}$ from vertical, particles stop slipping downward and begin to form a stationary bed along the annular bottom side. In view of the difference of cuttings transport mechanisms at different inclination scales, the entire borehole is divided into three segments according to the two critical inclination angles, i.e., the horizontal and near-horizontal section (horizontal section in abbreviation), transitional section, and vertical and near-vertical section (vertical section in abbreviation).

Assumptions for the model are, (1) homogeneous bubble flow is the unique flow pattern of foam fluid in the entire annulus, (2) the compressibility of foam drilling fluid completely depends on gas phase, (3) cuttings have constant particle diameter, circularity and uniform distribution in each flow layer, (4) the slip effect between gas phase and fluid phase is negligible, so is the mass transformation and energy exchange between fluid phase and solid phase, and (5) the rotation of drill string is not considered.

2.1 *Horizontal section*

The eccentric annulus in the horizontal section is assumed to have three layers with sharp interfaces, as shown in Fig.1.




1—Suspension layer, 2—Moving layer, 3—Stationary bed

Fig.1 Three-layer mechanical model ($\theta_{c2} \le \theta \le 90^{o}$)

2.1.1 Equations of continuity

The equations of continuity for solid phase and foam fluid are

$$A_1 v_1 C_1 + A_2 v_2 C_2 = A_a \overline{v} C_c \tag{1}$$

$$A_1 v_1 \left(1 - C_1\right) + A_2 v_2 \left(1 - C_2\right) = A_a \overline{v} \left(1 - C_c\right) \tag{2}$$

Geometric relation is

$$A_1 + A_2 + A_3 = A_a \tag{3}$$

where, $C_i$ ( $i$ = 1, 2, 3) are the mean cuttings volumetric concentrations for each layer, $C_c$ is the mean volumetric concentration of moving cuttings in the annulus, $A_i$ and $A_a$ are the annular sectional area of each layer and the total annular sectional area, $v_i$ and $\overline{v}$ are the average velocity of each layer and annular average velocity, respectively.

The entrapped particles in the moving layer and stationary bed are assumed to pack in cubic form, so

$$C_2 = C_3 = 0.52$$

$C_c$ is calculated by the equation

$$C_c = \frac{v_R}{\overline{v} A_3^*} \left[ \frac{\pi}{4} d_o^2 \left(1 - \phi\right) - 0.48 A_3^* \right] \bullet \left[ 1 - \left( \frac{d_i}{d_o} \right)^2 \right]^{-1} \tag{4}$$

where, $v_R$ is the rate of penetration, $\phi$ the formation porosity, $A_3^*$ the sectional area of stationary bed in the new wellbore grid, $d_i$ and $d_o$ are respectively the inside and outside diameter of the annulus.

One-dimensional diffusion equation for particles is

$$N_c \frac{\partial^2 C}{\partial y^2} + V_h \frac{\partial C}{\partial y} = 0 \tag{5}$$

Boundary conditions are

$$y = h_1 y = h_1 + h_2 h_2 \text{ , } \quad C_1 = C_2 = 0.52 \text{ ,}$$

$$y = d_o \text{ , } \quad C_1 = 0$$