PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 6, December 2017
Online English edition of the Chinese language journal

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(6): 1045–1052.

RESEARCH PAPER

Simulation of mud invasion and analysis of resistivity profile in sandstone formation module

FAN Yiren[1, 2, 3, *], WU Zhenguan[1, 2, 3], WU Fei[4], WU Junchen[1, 2, 3], WANG Lei[1, 2, 3]

1. School of Geosciences in China University of Petroleum, Qingdao 266580, China;
2. Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China;
3. CNPC Key Laboratory for Well Logging, China University of Petroleum, Qingdao 266580, China;
4. Suzhou Niumag Analytical Instrument Corporation, Suzhou 215163, China

Abstract: To investigate the dynamic invasion process of drilling fluid, the parameters of the physical model in laboratory were optimized based on numerical simulation and a physical simulation system for mud invasion in undisturbed zone was developed. Then, the experiment of fresh water invasion in sandstone formation was conducted to measure the radial resistivity and mudcake parameters over time, and a mudcake porosity and permeability calculation model with the invasion time was proposed based on the measurement. Finally, the numerical simulation results were compared and calibrated with the physical simulation results to find out the regularity of drilling fluid invasion under formation conditions. The results show that the mudcake forms quickly and the porosity and permeability of the mudcake decrease sharply after the beginning of drilling fluid invasion, and the invasion process is mainly controlled by the mudcake after a certain period. The mudcake parameters model developed in this study can depict the changes of mudcake parameters during the invasion process. The characteristics of radial resistivity profile under mud invasion are affected by sandstone physical properties, mudcake parameters and formation water salinity.

Key words: mud invasion; physical modeling; numerical simulation; mudcake; resistivity; porosity; permeability

Introduction

Due to the pressure difference between borehole and formation, mud filtrate invasion in permeable formations is commonly observed in over-balanced drilling. The corresponding liquid property changes in formations near the borehole have significantly added the difficulty in the well logging interpretation. Meanwhile, as the solid particles deposit and attach to the borehole wall, a low permeability mudcake would be formed to reduce drilling fluid loss[1], and only a limited amount of mud filtrate can displace formation fluid passing through the mudcake, this makes it possible to detect the original formation properties via well logging. In the last few decades, many researches have been done on correcting the effect of drilling fluid on logging data to extract true formation information.

In the early studies, focusing on mud filtration, core scale experiments and numerical simulation[2] were combined to the dynamic filtration of drilling fluid and mudcake build-up process by considering the effects of drilling mud composition and solid particle content etc[3–7]. To improve the accuracy of electric logging interpretation, the researchers have studied the radial conductivity changes of the formation during mud invasion[8]. Based on the experimental results and mudcake build-up model, the radial variation of water saturation and resistivity have been analyzed[9–11]. In thick permeable formation, the two dimensional numerical simulation taking into account the effect of gravity force was performed[12–13]. Through numerous numerical simulation and physical modeling, we have gained some knowledge on the invasion process of drilling fluid and mudcake build-up. However, limited by processing technology and economic consideration, most experiments currently are done on core plugs, which is different from the real drilling fluid invasion environment. Therefore, it is necessary to develop an invasion experimental system of the formation scale for real-time and direct monitoring of the whole invasion process[14–18], which is of great significance for revealing the invasion law of drilling fluid and the building and interpretation of electric logging model. In this study, we analyze the mudcake buildup process and radial resistivity profile in sandstone reservoirs by combining numerical simu-

Received date: 15 Jun. 2017; **Revised date:** 29 Sep. 2017.
*** Corresponding author.** E-mail: fanyiren@upc.edu.cn
Foundation item: Supported by the National Natural Science Foundation of China (41474100, 41674131, 41574118); the Fundamental Research Funds for the Central Universities (17CX06041, 15CX06008A); Graduate Innovation Project of China University of Petroleum (East China) (YCX2017004).

lation with physical modeling[19]. Firstly, the parameters of physical modeling system are optimized based on the numerical simulation. Through the calibration between the numerical simulation results against experiment data, the mudcake permeability is obtained. Finally, the original formation mud invasion characteristics are analyzed to provide a theoretical support for the model construction of well logging interpretation and electric logging correction in reservoirs.

1. Mud invasion experimental system establishing

Based on the two-phase flow and ion diffusion theory, the mud filtrate invasion process was simulated to optimize the size and other parameters of the formation module used in the experimental system. Then, with the established formation module scale mud invasion system, the mudcakes under different invasion stages were extracted. Finally, a new mudcake parameter measurement method was proposed to handle the difficulties in mudcake measurement, such as the low hardness.

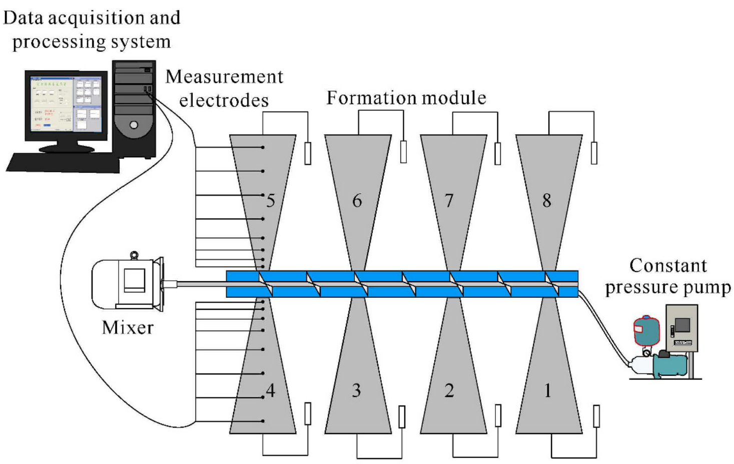
1.1. Experimental system

Limited by processing technology and cost, core size samples are widely adopted to study the mudcake buildup, drilling mud filtration and radial resistivity profile in the traditional drilling mud invasion experiments. However, mud filtration in core size experiments and borehole environments exhibit different patterns, i.e. linear and plane radial flow, respectively. Hence, using fan-shaped formation module to study the formation regularity of mudcake would be more consistent with the actual situation. On the other hand, the core size is too small for the radial profile parameter measurement like resistivity and pressure. In addition, it is hard to ensure the cores' coupling if several cores are linked to enlarge the radial length. Hence, a large core mud invasion experimental system in sandstone formation module scale has been designed in this study to simulate the realistic formation conditions, and reveal the invasion process of drilling mud.

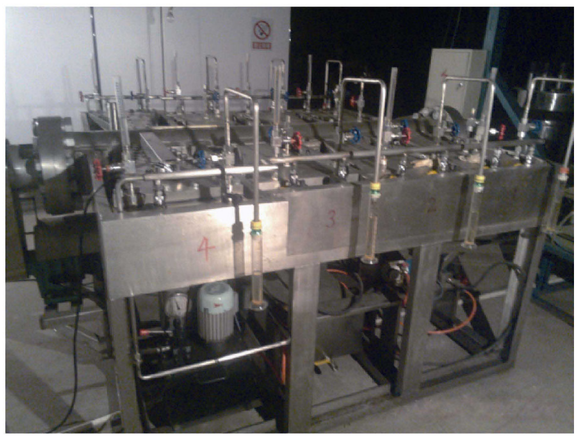
The newly developed invasion experimental system is shown in Fig. 1. The system includes four modules: borehole module, formation module, measurement module and data processing module. The borehole module is composed of mud circulation system and pressure maintaining system. The former is installed to prevent solid particles from deposition by continuous stirring with the internal mixer, while the latter is designed to keep constant borehole pressure and to guarantee the mud supplement. The formation module consists of invasion rooms, sealing rubber, and homogenous sandstone samples cut into fan shape. The measurement module includes a couple of devices to measure the sandstone resistivity, mud filtrate displacement flow, and mudcake parameters such as permeability and porosity. Finally, the recording data from the measurement module is simultaneously transmitted and plotted in the processing module. The experimental system in sandstone module designed in this study is closer to the realistic formation conditions. In addition, the borehole pressure, mud salinity and formation resistivity can be adjusted flexibly according to the research requirements.

1.2. Selection of formation model parameters

To make the experiment comparable with the mud invasion under original formation conditions, the sandstone size and other mandatory parameters used in experiment were selected with the help of numerical simulation. Since the invasion is severely affected by the radial extension, experiment with formation module scale sample is much better than than using core scale one. Limited by the processing technology and economic concerns, numerical simulation was taken to optimize the size of the formation module. We assumed that the formation permeability was 30×10^{-3} μm^2, formation porosity was 20%, oil saturation was 80%, immovable oil saturation was 20%, mudcake permeability was 3.0×10^{-6} μm^2, pressure difference between borehole and formation was 0.5 MPa. Based on the two-phase flow and ion diffusion theory, water saturation and salinity distribution were obtained. Then, the corresponding resistivity was calculated using Archie's Equation. Fig. 2 shows the water saturation distribution and radial resistivity profile of the formation at different invasion



(a) Schematic diagram of the mud invasion experimental system



(b) Main unit of the mud invasion experimental system

Fig. 1. Mud invasion experimental system.