Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 12, No. 1, 2024

A Review of Early Gas Intrusion Detection based on Multiphase Flow Model

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Abstract: High content gas reservoirs in deep reservoirs have complex pressure systems, and gas penetration occurs frequently during drilling, trip or other drilling operations. Due to the compressibility of gas and its easy solubility in drilling fluid, gas penetration in ultra-deep Wells is often sudden and hidden. In the early stage, it is difficult to find and fully alleviate gas invasion, which is very easy to induce blowout accidents. Accurate prediction and control of gas invasion is of great significance to prevent blowout accidents. In the past 20 years, the research of early gas invasion detection has made great progress. This paper aims to provide the latest progress of early gas intrusion detection based on transient multiphase flow, and make a comprehensive review of early gas intrusion detection. The specific contents include: 1. 2. The development of numerical simulation of early gas invasion detection is summarized. 3. The influencing factors of early gas intrusion detection modeling are analyzed. 4. The application of drift flux model in each flow pattern is introduced. 5. The importance of gas solubility and heat transfer in numerical simulation of gas penetration detection is analyzed. 6. The current development of early gas invasion detection was summarized and the future prospect was made.

Keywords: Multiphase Flow; Early Gas Penetration Detection; Drift Flux Model; Gas Solubility; Heat Transfer.

1. Introduction

Oil, coal and natural gas are important energy and strategic resources to ensure the stability of social life, the sustainable development of the national economy and national security. They are currently the world's primary energy source, accounting for more than 85% of the world's total energy production. China is rich in oil and gas resources, of which oil accounts for the largest proportion in energy consumption. It is expected that the domestic oil consumption will be 756 million tons in 2023, an increase of 5.1% [1].

With the increasing demand for oil resources, drilling operations are pushed deeper into the formation to explore more resources [2-5]. However, when drilling onshore or offshore, the high temperature and high pressure characteristics of deep formations put forward higher requirements for the safety of drilling operations. Gas invasion occurs when the hydrostatic pressure of drilling fluid is lower than the formation pressure. Due to the characteristics of high temperature and high pressure in deep formation and narrow mud density window, the pore pressure at the bottom of well is often higher than the hydrostatic pressure of drilling fluid, so gas invasion often occurs during drilling. When the gas enters the drilling fluid, it is in the form of dissolved or free gas. When the bubble begins to rise in the annulus, the decrease in hydrostatic pressure causes the bubble to expand, replacing the original heavy drilling mud. The hydrostatic pressure is reduced less than before the gas invasion. If effective degassing measures are not taken to allow the gas invading drilling fluid to continue to be pumped into the well, the pressure of the drilling fluid column will continue to drop, and finally the balance will be seriously out of balance, resulting in kick and even blowout, causing serious economic and environmental losses, and even endangering the life safety of workers. Blowout is a kind of vicious event that has occurred in both onshore and offshore oil and gas drilling, such as the blowout caused by hydrogen sulfide intrusion in Kaixian county, Chongqing [6] and the blowout of the Deepwater Horizon drilling platform in the Gulf of Mexico [7]. Therefore, it is important to respond to any signs of gas invasion as soon as possible. In the process of oil exploration, in order to drill without any accident, it is necessary to monitor gas intrusion in high-pressure Wells in time to control kick and prevent blowout.

2. Early Gas Invasion Monitoring Method

Early gas cut detection is an important part of well control technology. If formation gas is detected early enough to enter the wellbore, the flow of low-density fluid into the wellbore can be reduced, thereby reducing the maximum pressure difference generated at a given location in the well. It is difficult to determine the gas invasion, and improper handling may even lead to blowout accidents. Any warning signals from real-time logging data must therefore be taken into account. In drilling operations, there are two types of early gas intrusion detection methods: conventional methods and unconventional methods. Conventional methods rely on measuring drilling parameters (mud pool increment, wellbore inlet and outlet flow differential), while unconventional methods use advanced sensors and algorithms to detect changes in parameters. This section introduces the characteristics of each method, focusing on the advantages and limitations of numerical simulation in unconventional methods.

There are two conventional methods for early gas cut detection: the incremental detection of mud pool and the differential detection of wellbore inlet/outlet flow. In all gas penetration tests, data on reservoir increment, riser pressure, and mud return flow are systematized to monitor the fluid level in the well or reservoir, and increased volume is considered a possible indication of gas penetration. The increase of mud pool and the change of outlet flow rate during gas invasion are mainly caused by the rise of gas in wellbore and the continuous entry of new gas into wellbore. The development of this method mainly relies on the improvement of data acquisition technology, such as the improvement of flowmeter accuracy (the use of Coriolis flowmeter) and the rapid acquisition of drilling fluid properties [8]. However, the traditional monitoring method relies too much on the measurement of drilling fluid properties. As the drilling fluid properties increase with the lag time of the well depth, and the high-temperature and high-pressure characteristics of deep formation, the gas invaded by the formation has a high solubility in the drilling fluid, and it is difficult to detect the early gas invasion, resulting in obvious hysteresis in the monitoring. This defect greatly hinders the effective monitoring of early gas invasion by conventional methods.

In the unconventional early gas invasion detection methods, sensors have been gradually applied. In the published literature, various sensors have been used to detect gas penetration, including resistance technology, ultrasonic technology, pressure sensing technology, imaging technology, cable transmission technology, etc. [9-11]. These technologies are mainly used to detect riser and casing pressure, annular level and other parameters. Early gas penetration detection is complicated, and sensor data is crucial for detecting gas penetration size, flow pattern, temperature and bottom hole pressure, which all depend on the establishment of mathematical models such as numerical simulation of heat transfer, gas solubility and multiphase flow for early gas penetration detection based on empirical correlation. However, these models may have limitations due to the complex physical phenomena and flow behaviors involved. In order to obtain accurate and detailed results of early gas penetration detection, Sun et al. [12] suggested to consider two-dimensional or three-dimensional simulation analysis in the annulus. Nowadays, advanced computational fluid dynamics (CFD) is being used to calculate the interaction between multiphase flows in the virtual annulus geometry. The Navier-Stokes governing equation is solved by computational fluid dynamics model, which combines turbulence model and multiphase multiphase flow model, to achieve the simulation objective [13]. In CFD simulation, a suitable model is selected according to the expected flow state, and the three-dimensional control equation is solved [14]. However, turbulence modeling remains a challenging topic in the field of fluid dynamics. Although some progress has been made in describing single-phase flow turbulence, multiphase flows (especially those involving particles) still need to do more work, considering more parameters such as fluid properties, pipe geometry, multiphase flow parameters, etc., which can help improve the accuracy of turbulence models and reduce uncertainties. Comparative benchmark studies (experimentally validated) with different CFD software at the same time are necessary to determine their limitations in modeling several aspects of bubble transport phenomena (turbulence, particle deposition, particle tracking, and fluid-particle coupling). In addition, it is necessary to compare the accuracy of Euler-Euler and Lagrange-Euler methods for bubble transport models with different particle concentrations. At present, the ability of researchers to accurately predict and control multiphase flow phenomena and processes depends on proper description of flow phenomena and reasonable selection of mathematical models and numerical methods, and it is also necessary to develop and improve effective multiphase flow models to be applied in CFD to overcome the limitations of existing models [15].

3. Progress in Numerical Simulation of Early Gas Penetration Detection

The earlier the gas invasion is detected, the smaller the volume expansion of the invading gas, the smaller the change in bottom hole pressure, and the higher the probability of successful well control. Modeling of transient early gas penetration detection considering multiphase flow (mainly gas-liquid two-phase) is indispensable in the analysis of pressure profile, temperature profile and voidage. Therefore, through proper understanding of drilling fluid properties and planning for kick mitigation, bottomhole pressure can be accurately predicted and gas flow can be effectively blocked at an early stage. Only by selecting a suitable model can we accurately predict the phase fraction and the velocity distribution of the two phase fluid in the annulus.

Obrien[16] studied the solubility of gas in water-based and oil-based drilling fluids and found that the solubility of natural gas in oil-based mud was 10 to 100 times that in water-based mud. Thomas et al. [17] studied the gas intrusion detection model by using the isothermal model related to the solubility of saturated gas. The results show that the most reliable index of gas invasion in oil-based mud and water-based mud is the increment of mud pool, and because of the gas solubility, it is more difficult to detect gas invasion in oil-based mud than in water-based mud. However, most of the gas considered in previous studies is methane, and acidic gas is rarely considered. In most existing two-phase flow models describing gas intrusion, only conventional well control analysis of gas intrusion is considered. In fact, under high temperature and pressure conditions, the solubility of acidic gas in water-based mud is even higher than that of hydrocarbon gas in oil-based mud [18-21]. Rommetveit[22] studied various factors affecting natural gas invasion through dynamic simulation, such as drilling speed, drilling fluid flow, formation depth, reservoir permeability, formation pressure, etc. Assuming that the wellbore temperature varies linearly along the depth of the well, they studied two different types of gas intrusion, namely continuous formation gas intrusion and bottom-hole concentrated gas intrusion, and found that the mud pool increments were the same in both cases. Ma et al. [23] used the transient drift flux method based on conservation of mass and momentum to simulate gas penetration in oil-based drilling fluids, and calculated the solubility of methane in oil-based drilling fluids at different temperatures and pressures. Zhang[14] established a wellbore multiphase flow model considering gas dissolution and suspension, and analyzed the influence of gas dissolution and suspension in drilling fluid during overflow, shut-in and kill processes on wellbore multiphase flow. They concluded that the solubility of gas in drilling fluids is a critical factor that must be considered in planning and construction.

4. Factors Influencing Modeling of Early Gas Invasion Detection

Wellbore temperature is determined by heat transfer between drilling mud and formation, which affects interphase mass transfer and thermal physical parameters of fluid. The gas solubility is closely related to the wellbore pressure, which affects the free gas content and causes the change of multiphase flow pattern. The multiphase flow pattern determines the wellbore temperature and pressure distribution, which affects heat and mass transfer. Therefore, the evolution of multiphase flow in drilling fluid is a complex dynamic process, which is affected by various factors such as temperature, pressure, heat transfer rate, mass transfer rate, gas penetration rate and flow rate. The modeling of multiphase flow needs to obtain the constitutive equation according to pressure, temperature, gas-liquid velocity and each phase fraction, combined with the mass conservation equation, momentum conservation equation, energy conservation equation and the temperature-pressure-volume relationship of gas. Considering the flow pattern, gas solubility, heat and mass transfer, frictional pressure drop, thermal properties of drilling fluid and other important factors, a transient two-phase flow model was established. At present, a complex prediction method is needed to simulate the characteristics of transient multiphase flow and gas invasion fluid dynamics in wellbore annulus.

5. Summary

(1) The existing models basically assume that drilling fluid flows along the wellbore in one dimensional, ignoring the heat transfer between formation intrusive gas and drilling fluid and the thermal change caused by fluid phase transformation. These simplified assumptions will lead to the inaccuracy of early gas intrusion detection during HHP drilling.

(2) Existing early gas penetration detection simulators usually only consider the gas-liquid phase. In the actual drilling process, cuttings, hydrates and supercritical fluids are generated, and there will be a three-phase or even more multiphase equilibrium, phase slip and flow pattern evolution further increase the complexity of multiphase flow.

(3) Most of the existing models use constant fluid rheological characteristics. High temperature conditions will lead to fluid expansion in the wellbore, and high pressure conditions will lead to fluid contraction, thus affecting gas solubility, interphase mass transfer, heat transfer and other behaviors. Failure to consider these two opposite effects will result in errors in the calculation of bottom-hole pressure. Accurate calculation of fluid thermodynamic properties related to temperature and pressure is the key to predicting early gas invasion.

(4) The current EGKD methods have problems such as limited detection time, reliance on manual judgment, complex modeling, and low safety. In the future, EGKD method will definitely combine data analysis, artificial intelligence, fluid mechanics and multiphase flow theory to develop in the direction of intelligence, automatic, reliable and efficient

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