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Research Article

Propagation velocity and time laws of backpressure wave in the wellbore during managed pressure drilling ☆

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Abstract

When gas invasion, especially overflow, occurs at the bottom hole in the process of managed pressure drilling (MPD), it is common to apply backpressure on the wellbore by adjusting the backpressure pump and throttle valve, so as to rebuild bottom hole pressure balance. If it is still thought that the wellhead backpressure is loaded to the bottom hole instantaneously, there will be larger errors between the calculated wellbore parameters and the actual wellbore flow parameters, which will result in well control failure and even well blowout. In this paper, a pressure wave propagation equation suitable for the gas–liquid two-phase flow in the annulus was established based on the global averaged gas–liquid two-phase flow model to investigate the propagation velocity and time of backpressure wave in the wellbore. Then, gas–liquid interaction was introduced to carry out coupling solution on the equation set. It is shown that pressure wave velocity increases with the increase of drilling mud density, but decreases with the increase of void fraction and virtual mass force coefficient. It changes drastically at first, and then slows down. What's more, when the void fraction is greater than 0.1 or the virtual mass force coefficient exceeds 0.2, the momentum between gas phase and liquid phase is fully exchanged, and the pressure wave velocity decreases slowly, approaching a stable value. In Well Penglai 9 in the Sichuan Basin, for example, the average time of single pressure wave propagation is about 50 s, and the total propagation time of 4 rounds is about 200 s, which accounts for more than 67% of the total time of system control response. It is indicated that the propagation velocity and time of the pressure wave in the annulus calculated by this method can greatly improve the accuracy of managed pressure response time of MPD drilling system and the control precision of adaptive throttle valve.

Keywords: Managed pressure drilling (MPD); Gas invasion; Gas–liquid two-phase flow model; Virtual mass force coefficient; Gas–liquid two-phase flow; Pressure wave propagation equation; Pressure wave velocity; Managed response time

0. Introduction

Managed pressure drilling (MPD) is a drilling technology that can precisely control the bottom hole pressure and can effectively solve lost circulation, well kick and other drilling safety problems triggered by a narrow safety density window in deep complex formations [1–3]. Currently, there are mainly three ways to control the bottom hole pressure by MPD [4–6]. The first way is to adjust the drilling mud density. In this way, it is necessary to prepare new drilling mud again, so longer time will be spent, and the quantity of formation fluids invading the wellbore is larger in this period. The second way is to adjust the capacity of the inlet mud pump, and increase the flow velocity

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of the drilling mud in the annulus so as to increase the friction pressure loss to balance the bottom hole pressure. This way is not only affected by the certified capacity of the mud pump, but also contributes little to the adjustment of bottom hole pressure. The third way is to adjust the backpressure pump and throttle valve so as to apply backpressure on the wellbore [7,8], which is the most effective, fastest and most common way to rebuild bottom hole pressure balance. In the case of high pressure reservoir, under the condition of determined drilling mud system and drilling equipment, when formation fluid invasion, especially gas invasion, is monitored in the annulus, the throttle valve is adjusted to produce backpressure at the wellhead to act on the whole wellbore, so that the bottom hole pressure can be balanced gradually with the formation pressure, thus slowing down until restraining the ongoing invasion of formation gas into the wellbore. Compared with the former two ways, this way has a significant advantage in controlling the bottom hole overflow. The backpressure produced by adjusting the wellhead valve is propagated from wellhead to bottom hole in the form of pressure wave, which requires a certain period of time, that is, the propagation time of pressure wave in wellbore. According to related literature [9], when gas invasion does not occur, the flow in the annulus is a single liquid-phase flow of pure drilling mud, and the pressure wave is propagated from wellhead to bottom hole quickly at a velocity of nearly 1200 m/s. When gas invasion occurs, the formation gas invades the wellbore, and the annulus changes from the original pure liquid-phase to gas–liquid two-phase flow. Due to the compressibility of gas and the momentum exchange of interface between gas and liquid phases, the velocity of pressure wave decreases sharply, and the wellhead backpressure wave often needs tens of seconds and even longer time to arrive at the bottom hole [10], during which more formation fluids invade the wellbore. If it is simply thought that the wellhead backpressure is loaded to the bottom hole instantaneously, without considering the propagation time of pressure wave in wellbore and lag of the MPD control response time, then it will be unable to accurately calculate the volume of formation fluids that have invaded the wellbore, especially gas content, and there will be larger errors between the calculated wellbore multi-phase flow parameters and the actual wellbore flow parameters, which may result in well control failures and even well blowouts or other serious drilling accidents. Therefore, studying the propagation velocity and time of the wellhead backpressure in the annulus in the form of pressure wave after MPD gas invasion can greatly improve the accuracy of managed pressure response time of MPD system and the control precision of adaptive throttle valve, and provide a theoretical support for the precise control of MPD.

1. Establishment of backpressure wave propagation model in gas–liquid two-phase flow of wellbore

1.1. Backpressure wave propagation model and equation

In the two-fluid model [11,12], both gas phase and liquid phase are regarded as a continuous medium filling the whole annular flow field area, and the continuity equation and momentum equation of the two phases are written respectively; then the interaction between gas and liquid interfaces (mass exchange and momentum transfer) is used to couple the equation sets. It is assumed that the gas phase and the liquid phase are continuous media within their own local flow field areas, and thus other artificial assumptions are not needed. This model is applicable to the annular void fraction caused by different degrees of gas invasion and various flow patterns, and the solution obtained contains more comprehensive wellbore flow information. So it is a relatively perfect model for studying the gas–liquid two-phase flow in wellbore after gas invasion. In the global averaged two-fluid model, the advantages of the time averaging method and space averaging method in the two-fluid model are synthesized, and the shortcomings of the two methods are overcome. This model has the strictest derivation process and the most complete equation structure among multiple averaging methods, which can well model the transient phenomena and the propagation laws of pressure wave in gas–liquid two-phase flow of wellbore after gas invasion. The authors used the global averaged two-fluid model, and introduced the source item for the momentum exchange between gas phase and liquid phase and the shear force of the outer wall of drill rods and the well wall to couple the equation set, and establish a propagation equation set of pressure wave in the annular gas–liquid two-phase flow of wellbore.

It is assumed that the annulus of wellbore is a uniform cross section. Then for the gas–liquid two-phase flow of wellbore at any dip angle α (Fig. 1), there is not enough time for the mass and energy between gas and liquid phases to exchange because the propagation process of pressure wave is a transient process. Thus it is believed that there is no phase change or mass and energy exchange between gas and liquid phases. Therefore, the momentum exchange between the two phases is considered primarily. Because the wellbore annulus radius is very small as compared to the axial length of wellbore, it can be ignored [13,14]. Thus the three-dimensional gas–liquid two-phase flow of wellbore can be regarded as the one-

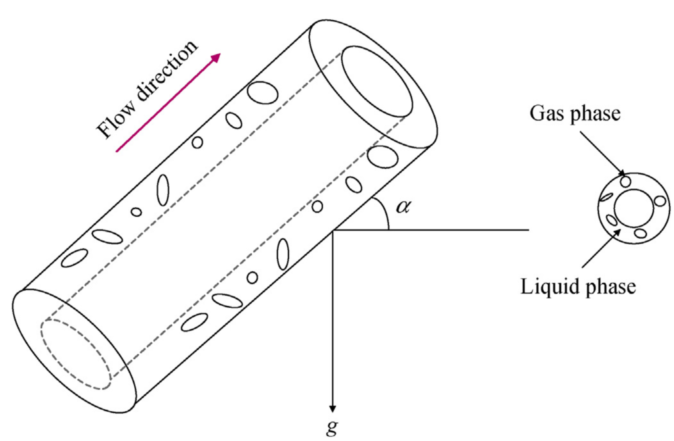

Fig. 1. Schematic diagram of the gas–liquid two-phase flow model of wellbore in the annulus.