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Investigation of pressure wave propagation and attenuation characteristics in wellbore gas-liquid two-phase flow

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A B S T R A C T

Pressure waves have many important applications in the oil and gas drilling engineering field. This paper aims to discuss the propagation and attenuation of pressure waves transmitted in wellbore gas-liquid two-phase flow. In this study, a mathematical model is proposed that estimates the pressure wave propagation and attenuation in wellbore two-phase fluid flow. The model is based on a two-fluid model and considers the interactions between two phases, wall shear force, and gravitational effect. The wave speed and attenuation coefficient are calculated and compared to previous experimental results. The comparison of the results shows satisfactory compliance. Based on the model, the effects of void fraction, angular frequency, system pressure, and temperature on wave speed and attenuation coefficient are discussed. The results indicate that pressure wave dispersion is obvious in wellbore two-phase fluid flow. The wave speed first decreases with an increase in the void fraction and then exhibits a flat transition. Next, the wave speed increases notably after the void fraction exceeds 90%, showing a characteristic U-shape curve. The pressure wave attenuation shows the inverse variation trends than that of wave speed. Lower angular frequency and temperature, and higher system pressure are observed to benefit the transmission of a pressure wave in wellbore two-phase flow. Furthermore, the propagation and attenuation behaviors of pressure waves in wellbore two-phase flow during aerated underbalanced drilling are discussed as a case study. The pressure wave attenuation rises with respect to the gas injection rate. The amplitude of the pressure wave at the wellhead decreases to 8.1% of the initial value when the gas injection rate reaches 13 m^3 min^{-1}. This wave amplitude is almost undetectable during drilling operations. This is the cause of failure for mud pulse telemetry in aerated underbalanced drilling. Stronger attenuation is observed when the pressure wave travels close to the wellhead.

1. Introduction

The use of pressure waves is beneficial to drilling engineering in many aspects. The best-known application of pressure waves is called mud pulse telemetry, which transmits directional and geological information through the drilling fluid to the surface in real-time with the use of coded pressure pulses (Lea and Kyllingstad, 1996; Namuq et al., 2013; Li et al., 2015). In addition, pressure waves have important applications in other areas, such as gas influx detection, and dynamic well control response in managed pressure drilling (Codazzi et al., 1992; Stokka et al., 1993; Denney, 2015; Vajargah and Oort, 2015; Feng et al., 2015). In these and other applications, it is necessary to estimating pressure wave propagation and attenuation characteristics in the wellbore drilling fluid flow. There are robust theories concerning the propagation characteristics of the pressure wave in wellbore single-phase flow, but for gas-liquid two-phase flow commonly encountered in oil and gas drilling engineering, the characteristics of pressure wave propagation are far more complicated. The combination of high compressibility of the gas phase and intensive interactions between the gas-liquid two-phase yields a lower wave speed and relatively high attenuation, while the pressure wave propagates in two-phase mixtures. Further investigations are needed to understand the

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propagation and attenuation behaviors of pressure waves in wellbore two-phase flowing mixtures, which is beneficial for extending the application of the pressure wave in drilling engineering.

The behaviors of pressure wave propagation and attenuation in wellbore two-phase fluid have been investigated by some researchers. Falk (1998) discussed the pressure wave behaviors through wellbore gas-liquid mixtures. He found that the pressure wave propagation in gas-liquid mixtures is strongly dependent on temperature, pressure, and gas content. Wu et al. (2015) analyzed the effect of the frequency and multi-boundary conditions on the mud pressure wave in a non-Newtonian drilling fluid. Liu et al. (2007) presented a multiphase flow formula to estimate dynamic transmission behaviors of pressure pulses in wellbore multiphase flow. Only the effects of wall shear force and compressibility of gas phase were considered in the proposed model. The interactions between two phases were also neglected, which play an important role in the wave speed in wellbore two-phase flow. The multiphase flow formula proposed in their work is still a single-phase model. Lin et al. (2013) analyzed the wave speed of pressure waves in wellbore two-phase mixtures induced by unsteady operations in managed pressure drilling. However, pressure wave attenuation, which is an important characteristic of pressure wave transmission in two-phase flow, is merely mentioned in the work above. Li et al. (2012) proposed a real multiphase flow model estimating the pressure pulses attenuation along drill strings in aerated drilling. In this model, the effects of the interactions between two phases, wall shear force, and inclination on pressure pulses were considered. However, the model by Li et al. (2012) is restricted to the pressure wave propagation in wellbore bubbly flow and only involved theoretical studies with no experimental data for verification of the model. The current understandings of the pressure waves in wellbore gas-liquid two-phase flow are not satisfactory.

The flow of the gas-liquid mixture in wellbore discussed in this study is a kind of typical two-phase pipe flow. In recent decades, the behaviors of pressure wave propagation in a pipe with gas-liquid two-phase flowing mixtures have been investigated by many researchers both experimentally and theoretically. The problem was first investigated using empirical methods due to the complexity of the pressure wave propagation in two-phase flowing fluid. Carstensen and Flody (1947) were the first to measure the wave speed of pressure wave through the liquid containing bubbles. Karplus (1958), Hsieh and Plesset (1961), and Henry et al. (1971) also experimentally obtained the wave speed in bubbly flow. Keiji et al. (1971a), Mori et al. (1975), and Legius et al. (1997) tested the wave speed of a pressure wave travelling in slug flow. Ruggles et al. (1988) measured the dispersion characteristic of a pressure wave propagating in gas-liquid two-phase fluid flow. They found that the wave speed depends on the frequency content of the imposed wave. Wang et al. (2000) and Huang et al. (2005) tested the attenuation of a forced pressure wave propagating in an upward bubbly pipe flow. The theoretical investigation of pressure wave propagation in two-phase fluid flow began with the expression developed by Campbell and Pitcher (1958) for the wave speed of a pressure wave propagating in a tube with a mixture containing liquid and gas bubbles. The compressibility of the liquid phase and interactions between two phases were neglected in their work. Bryant (1975) extended the work of Campbell and Pitcher by including effects of temperature change across the wave. Wallis (1969) proposed a model for estimating the wave speed of a pressure wave in a horizontal pipe with bubbly flow and separated flow. Nguyen et al. (1981) analyzed the wave speed in four different flow regimes by means of the elastic theory. Keiji et al. (1971b) investigated the effect of slip between two phases on the wave speed of a pressure wave propagating in two-phase flowing mixtures. They observed that slip reduces the inertial effect and consequently increases the wave speed. Mori et al. (1975) studied the wave speed of finite amplitude pressure waves in tubes containing two-phase mixtures. The reflection behavior of a pressure wave was also discussed in their work. Chung et al. (1992) derived a model for simulating the dispersion and attenuation characteristics of a pressure wave in bubbly flow with low void fraction. They discussed the effects of interfacial area density on pressure wave attenuation. Ichihara and Kameda (2004) investigated the frequency-dependent characteristic of a pressure wave in bubbly flowing mixtures. Huang et al. (2004), Xu and Gong (2008), Li et al. (2011) investigated the wave speed of a pressure wave in two-phase flow based on a two-fluid model. Martin and Padmanabhan, 1975, Tan and Bankoff (1983), Chaudhry et al. (1990), Guinot (2001), and Leon et al. (2008) analyzed the propagation characteristics of pressure waves in bubbly flow using numerical methods. However, these investigations mainly focused on the air-water system, and the understandings of pressure wave attenuation are not adequate. Essentially, the drilling fluid in drilling engineering can be regarded as a typical viscous fluid. The interactions between two phases are more important in the pressure wave propagation and attenuation in the wellbore gas-liquid two-phase fluid flow considered in this study than that in the traditional air-water mixtures. The influence of temperature change on pressure wave propagation and attenuation behaviors should not be neglected. However, there is only scarce information in previous investigations available for the author's present work.

In this paper, a new method of identifying pressure wave propagation and attenuation in wellbore gas-liquid two-phase flow. Based on the two-fluid model, a mathematical model describing pressure wave propagation and attenuation behaviors in wellbore two-phase flow has been derived using linear perturbation theory. The interactions between the gas-liquid phases, wall shear force, and gravitational effect are considered in the model. Model validation is conducted using previous experimental results. The effects of the void fraction, system pressure, angular frequency, and temperature on pressure wave propagation and attenuation are analyzed. As a case study, the propagation and attenuation behaviors of a pressure wave in wellbore during aerated underbalanced drilling operations has been discussed in detail.

2. Mathematical model

In this paper, a one-dimensional mathematical model, based on the traditional two-fluid model, is developed for estimating the pressure wave propagation and attenuation in wellbore gas-liquid two-phase fluid flow. Analytical formulas were derived for wave speed and attenuation coefficient using linear perturbation theory.

To formulate the propagation and attenuation characteristics in wellbore gas-liquid two-phase flow, the following assumptions were introduced:

- The gas-liquid two-phase flow in wellbore is considered one-dimensional.
- The two phases are at the same pressure at all times.
- The pressure wave transmission is considered an irreversible adiabatic process.
- The liquid phase is incompressible.
- The distortion and nonlinear effects of pressure wave are neglected.
- The gas-liquid two-phase flow is at rest far ahead of the wave front.
- The gas phase obeys the ideal gas law.
- Mass transfer between the two phases is neglected.