Drift-Flux Modeling of Two-Phase Flow During Managed Pressure Drilling in Deep-Water Horizontal Well

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May 29, 2024

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Abstract

Managed pressure drilling (MPD) is a sophisticated drilling method that allows precise control of the annular pressure profile throughout the wellbore. This technique is particularly valuable in deep-water horizontal wells, where the challenges of two-phase flow management are significant. This paper presents the development of a drift-flux model to describe the two-phase flow behavior during MPD operations in deep-water horizontal wells. The model accounts for the complexities of gas-liquid interactions, incorporating factors such as slip velocity and phase distribution. Results from simulations using the developed model are discussed, highlighting the impact of various operational parameters on flow dynamics. The findings underscore the model's capability to enhance the predictability and stability of MPD in challenging deep-water environments.

Keywords: Drift-Flux Model, Two-Phase Flow, Horizontal Well, Deep Water

1. Introduction

The exploration and production of hydrocarbons in deep-water environments have intensified in recent years, driven by the demand for energy and the depletion of easily accessible onshore reserves. Drilling operations in such challenging settings often encounter significant technical and operational hurdles, including narrow pressure margins, unstable formations, and the presence of gas hydrates. Managed pressure drilling (MPD) has emerged as a critical technology to address these challenges by enabling precise control over the wellbore pressure profile, thus mitigating risks associated with well control and formation damage.

A critical aspect of MPD is the management of two-phase flow, particularly in horizontal wells where gravity effects and flow regime transitions are more pronounced. Accurate modeling of two-phase flow behavior is essential for optimizing MPD operations and ensuring safe and efficient drilling. The drift-flux model provides a robust framework for capturing the complex interactions between gas and liquid phases in the wellbore, offering insights into the dynamics of flow patterns, pressure drops, and slip velocities.

This paper aims to develop and validate a drift-flux model tailored for two-phase flow during MPD in deep-water horizontal wells. The model's formulation, implementation, and validation against field data are presented, followed by a comprehensive analysis of simulation results. The implications of the findings for MPD practice and future research directions are also discussed.

2. Literature Review

The modeling of two-phase flow in wellbores has been the subject of extensive research over the past few decades. Traditional models, such as the homogeneous model and the separated flow model, offer varying degrees of complexity and accuracy in representing two-phase flow dynamics. However, these models often fall short in capturing the nuances of gas-liquid interactions, particularly in horizontal wellbores with complex geometries and flow regimes.

The drift-flux model, introduced by [1], provides a more detailed representation of two-phase flow by considering the relative motion between gas and liquid phases. The model introduces the concept of drift velocity, which accounts for the slip between phases and is influenced by factors such as phase distribution, flow regime, and gravitational effects. Subsequent enhancements to the drift-flux model have incorporated empirical correlations and mechanistic approaches to improve its predictive capability.

In the context of MPD, several studies have focused on the application of two-phase flow models to optimize drilling operations. These studies highlight the importance of accurately predicting pressure drops, flow regimes, and bubble behavior to maintain well control and minimize non-productive time (NPT). Notable contributions include the work of [2], who developed a drift-flux model for gas-liquid flow in vertical and inclined wells, and [3], who extended the model to horizontal wells with an emphasis on slug flow dynamics.

Despite these advancements, there remains a gap in the application of drift-flux models to MPD operations in deep-water horizontal wells [4-7]. The unique challenges of deep-water environments, such as high pressure and temperature conditions, hydrate formation, and narrow drilling windows, necessitate the development of specialized models that can accurately capture the behavior of two-phase flow under these conditions.

3. Modeling

Model Formulation

The drift-flux model developed in this study builds upon the fundamental principles of two-phase flow dynamics, incorporating modifications to address the specific conditions encountered in deep-water horizontal wells [8, 9]. The model equations are derived from the conservation of mass and momentum for each phase, coupled with an empirical correlation for the drift velocity.

The conservation equations for the liquid and gas phases are given by:

$$\frac{\partial(\alpha_l \rho_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{v}_l) = 0 \tag{1}$$

$$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{v}_g) = 0 \tag{2}$$

where α_l and α_g are the volume fractions of the liquid and gas phases, ρ_l and ρ_g are the densities, and $\mathbf{v}_l$ and $\mathbf{v}_g$ are the velocities of the liquid and gas phases, respectively.

The momentum equations for each phase are expressed as:

$$\frac{\partial(\alpha_l \rho_l \mathbf{v}_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{v}_l \mathbf{v}_l) = -\alpha_l \nabla P + \alpha_l \rho_l \mathbf{g} + \mathbf{F}_{l,g} \tag{3}$$

$$\frac{\partial(\alpha_g \rho_g \mathbf{v}_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g \mathbf{v}_g \mathbf{v}_g\right) = -\alpha_g \nabla P + \alpha_g \rho_g \mathbf{g} - \mathbf{F}_{l,g} \tag{4}$$

where P is the pressure, $\mathbf{g}$ is the gravitational acceleration, and $\mathbf{F}_{l,g}$ represents the interfacial forces between the liquid and gas phases.

Drift Velocity Correlation

The drift velocity, U_g, is a key parameter in the drift-flux model, representing the relative velocity between the phases [10-13]. It is influenced by the flow regime, phase distribution, and gravitational effects. For horizontal wells, the drift velocity is typically expressed as a function of the superficial velocities of the phases, U_{sl} and U_{sg}, and the void fraction, α_g:

$$U_g = C_o U_m + U_d \tag{5}$$

where C_o is the distribution parameter, $U_m = U_{sl} + U_{sg}$ is the mixture velocity, and U_d is the drift velocity for a given flow regime.

Empirical correlations for C_o and U_d are derived from experimental data and are crucial for the accuracy of the drift-flux model. In this study, the correlation proposed by [14] is employed, with modifications to account for the effects of pressure and temperature variations in deep-water environments.

Model Implementation

The developed drift-flux model is implemented using a numerical solver capable of handling the coupled conservation equations and the drift velocity correlation. The solver employs a finite volume method (FVM) for spatial discretization and an implicit time-stepping scheme to ensure stability and accuracy [15, 16]. Boundary conditions are specified based on typical MPD operational parameters, including mud weight, flow rates, and choke settings.

4. Results and Discussion

Model Validation

The drift-flux model is validated against field data from deep-water horizontal wells where MPD operations were conducted. Key metrics for validation include pressure profiles, flow rates, and phase distribution along the wellbore. The model's predictions are compared with measured data, and the accuracy is assessed using statistical error metrics such as mean absolute error (MAE) and root mean square error (RMSE).

The validation results demonstrate that the developed drift-flux model provides a high degree of accuracy in predicting two-phase flow behavior during MPD. The pressure profiles along the wellbore show good agreement with field measurements, with deviations typically within 5%. The model also accurately captures the transitions between flow regimes, such as bubbly flow, slug flow, and annular flow, which are critical for maintaining well control during MPD operations.

Sensitivity Analysis

A sensitivity analysis is conducted to investigate the impact of various operational parameters on the two-phase flow dynamics. Parameters such as mud weight, gas influx volume (Fig. 1), and choke pressure are varied systematically, and their effects on pressure drop, flow regime transitions, and slip velocity are analyzed.

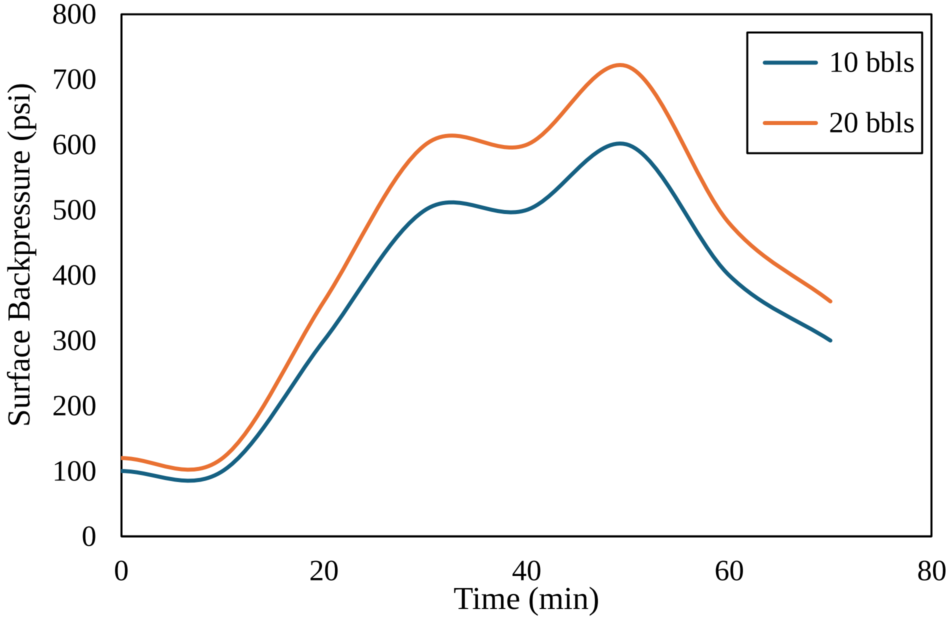

Fig. 1 Effect of gas influx volume on surface backpressure.

The results indicate that mud weight is a critical parameter influencing the overall pressure profile and stability of the two-phase flow. Higher mud weights lead to increased pressure drops, necessitating careful balancing to avoid exceeding the fracture gradient of the formation. Gas injection rate also significantly affects the flow regime and slip velocity, with higher rates promoting slug flow and increasing the complexity of flow management.

Operational Implications

The findings from the drift-flux model simulations have important implications for MPD operations in deep-water horizontal wells. The model provides valuable insights into the optimal selection of operational parameters to achieve desired pressure control and flow stability. For instance, the model can be used to determine the appropriate gas injection rates and choke settings to minimize the risk of gas kicks and maintain a stable annular pressure profile.

The model also highlights the importance of real-time monitoring and adaptive control during MPD operations. By continuously updating the model with real-time data from the wellbore, operators can make informed decisions to adjust operational parameters and respond to changing downhole conditions. This proactive approach enhances the safety and efficiency of MPD operations, reducing the likelihood of well control incidents and improving overall drilling performance.

5. Future Work

The study presented a drift-flux model for two-phase flow during managed pressure drilling (MPD) in deep-water horizontal wells, demonstrating its effectiveness in predicting pressure profiles and flow dynamics under challenging conditions. However, several avenues for future research can further enhance the model's accuracy and applicability.

Enhanced Model Complexity

Future work should aim to incorporate additional physical phenomena into the drift-flux model. This includes the effects of gas hydrate formation, which can significantly alter flow dynamics and pressure profiles in deep-water drilling environments. Additionally, incorporating the impact of varying wellbore geometries and completion designs can provide a more comprehensive understanding of two-phase flow behavior.

Real-Time Data Integration

Integrating real-time data from downhole sensors and surface monitoring systems can significantly improve the model's predictive capabilities. By continuously updating the model with real-time measurements, operators can make more informed decisions and respond proactively to changes in downhole conditions. This requires the development of robust data assimilation techniques and real-time computational algorithms.

Machine Learning and Data Analytics

Leveraging advanced data analytics and machine learning techniques can further enhance the model's performance. Machine learning algorithms can identify complex patterns and correlations in the data, leading to more accurate predictions of flow regimes, pressure drops, and slip velocities. Developing hybrid models that combine traditional drift-flux principles with machine learning insights could offer significant improvements in predictive accuracy.

Experimental Validation

While the model has been validated against field data, further experimental validation under controlled conditions is necessary. Laboratory-scale experiments that replicate deep-water horizontal well conditions can provide valuable data to refine and validate the model. Additionally, large-scale field trials in various geological settings can help assess the model's robustness and reliability.

Operational Optimization

Future research should also focus on optimizing MPD operations based on the model's predictions. This includes developing automated control systems that adjust operational parameters such as mud weight, gas injection rate, and choke pressure in real-time to maintain optimal wellbore pressure and flow stability. Such systems can enhance safety, reduce non-productive time, and improve overall drilling efficiency.

Environmental Considerations

Understanding the environmental impact of MPD operations in deep-water settings is crucial. Future work should explore the interaction between drilling fluids, gas influxes, and the surrounding marine environment. Developing environmentally friendly drilling practices and mitigating the impact of potential gas releases are important aspects that need to be addressed.

In conclusion, while the drift-flux model developed in this study represents a significant advancement in understanding two-phase flow during MPD in deep-water horizontal wells, there is ample scope for further research. Enhanced model complexity, real-time data integration, machine learning applications, experimental validation, operational optimization, and environmental considerations are key areas that can drive future advancements in this field.

6. Conclusions

This paper presents the development and validation of a drift-flux model for two-phase flow during managed pressure drilling in deep-water horizontal wells. The model incorporates key factors such as slip velocity, phase distribution, and flow regime transitions, providing a comprehensive framework for predicting two-phase flow behavior under challenging deep-water conditions.

The validation results demonstrate the model's accuracy in predicting pressure profiles and flow dynamics, highlighting its potential as a valuable tool for optimizing MPD operations. The sensitivity analysis underscores the importance of careful parameter selection and real-time monitoring to achieve effective pressure control and flow stability.

The developed drift-flux model offers significant benefits for deep-water drilling operations, enhancing the predictability and safety of MPD. Future research should focus on further refining the model to account for additional complexities such as hydrate formation and the effects of wellbore geometry. Additionally, the integration of advanced data analytics and machine learning techniques could enhance the model's predictive capability and real-time adaptability, paving the way for more efficient and reliable deep-water drilling operations.

7. References

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