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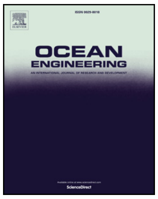

Hydrodynamic simulation of multi-sized high concentration slurry transport in pipelines

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ABSTRACT

A steady-state three-dimensional multiphase hydrodynamic model based on the kinetic theory of granular flow is developed to investigate the distributions of solid concentration, flow velocity, granular pressure, and wall shear stress in multi-sized slurry (two particle sizes, $d_p = 0.125$ mm and 0.44 mm, equal fraction by mass) transport by pipelines ($D = 54.9$ mm). The trends of the variation in transport properties with varying efflux particle concentrations ($C_{vf} = 20\%$, 30%, 40%, and 50%) and flow velocities ($v = 2$, 3, 4, and 5 m/s) are studied, and the effects of other different-sized particles on characteristics are modeled. Simulation results agree well with the corresponding experimental results in literature. The simulation results show that coarse and fine particle phases have different characteristics in each operating condition. The degree of deviation of the characteristics of different-sized particles increases as solid concentration or mixture velocity decreases. Additionally, the distinct effects of near-wall lift force and particle–wall collision on the characteristics of different-sized particles in multi-sized slurry are observed. The results obtained in this work elucidate the characteristics of different-sized particles in multi-sized slurry and provide a solid foundation for studying the mesoscopic processes of slurry transport by pipelines.

1. Introduction

In the last few decades, the pipeline transport of particulate materials has been promoted in dredging because pipelines are insulated from the environment and can be run in uninterrupted mode to reduce investment, operating costs, achieve high efficiency, energy saving, environmental protection, and easily implement optimized control. This method has been widely applied in several fields such as coal, metallurgy, and mining. According to statistics, pipeline transport in the dredging industry has contributed hundreds of billion dollars to the global economy in recent years. In addition, pipelines are considered as the tool with the most potential in emerging markets such as ocean mining.

In the past few decades, most studies on slurry pipeline transport have focused on the prediction of friction loss and critical velocity (no stable particle bed, the lowest pressure loss point). In recent years, enterprises have focused on the increase in operation cost caused by pipeline wear and maintenance. Generally, industrial slurry operates in the heterogeneous regime for economic benefit, in which the solid concentration in the lower half of a pipe is higher than that in the upper half owing to the gravitational effect. Thus, the wear of the bottom of the pipe is worse. To improve safety performance and enhance economic returns, pipelines are rotated according to pipeline abrasion level. Therefore, the knowledge of slurry concentration and velocity distributions, which leads to accurate prediction of the degree of pipeline wear, is an effective method of ensuring the safety of construction and improving economic benefits.

Existing models of slurry pipeline transport can accurately predict parameters such as pressure drop, particle settling velocity, and solid concentration distribution under different operating conditions using pipe diameter, particle size, slurry concentration etc. However, most of these models are empirical formulae based on dimensionless parameters, such as excess pressure, Froude number, and solid concentration derived from experimental data, or semi-empirical formulae based on the theory of gravity, energy, etc. It is impossible to characterize performance in theory, such as the turbulence intensity and particle momentum exchange in pipelines; however, these microscopic characteristics significantly affect pipeline characteristics in several cases with a variety of graded particles of multiple sizes. Understanding the changes in these parameters at different positions within a pipeline is

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critical for improving the understanding of the microscopic characteristics (such as pipes wear, energy loss, and slurry flow regime) in slurry pipeline transport.

Existing models cannot accurately predict the particle concentration distribution close to the bottom of a pipe, particularly when the maximum concentration of coarse particles deviates from that observed at the bottom of a pipe in the experiment performed by Kaushal and Tomita (2007). However, the solid concentration distribution close to a pipe wall determines the local solid pressure, wall shear stress, and friction resistance. Moreover, it is a critical factor in pipeline wear. Thus, accurate prediction of the solid concentration distribution, particular close to a pipeline wall, is the key to predicting pipeline wear and calculating friction resistance.

The knowledge of solid concentration, velocity distribution, and their variation in a pipe under different conditions is important for understanding the mechanism of pressure drop and predicting the degree of wear in pipelines. In addition, it is important for improving economic efficiency.

With the development of computer technology, computational fluid dynamics (CFD) has been widely applied for predicting the properties of pipeline transported slurry. In addition, the improvement in calculation methods makes CFD faster, more convenient, and more adaptable to engineering applications. Even though CFD is still in the developing stage for solid–liquid two-phase flow (most models refer to the gas–liquid two-phase flow theory), it is relatively well developed in terms of velocity distribution and solid concentration distribution simulations. In view of the current status of CFD technology, a three-dimensional (3D) CFD model based on the granular kinetic theory is established for a horizontal pipeline. The results obtained using the model are compared with published experimental results to study the variation in velocity distribution and concentration distribution with particle concentration, particle size, slurry velocity, and pipe diameter. The next section provides a brief review of the existing work in this field.

2. Previous work

In the last few decades, extensive research has been performed on slurry pipeline transport. However, the primary direction of research has always been pressure drop and critical velocity, which are typically given by the Durand (1952) formula. This formula is based on experimental data and is used by the majority of the European dredging industry. Wilson and Addie, 1997 formula is widely used by the dredging industry of the Americas. The two-phase flow model developed by Wasp et al. (1977) considers particle concentration distribution in transport processes. The formula proposed by Turian and Yuan (1977) uses different dimensionless parameters to fit experimental data. Doron and Barnea (1993) proposed a three-layer model based on mechanical balance. The formula developed by Lahiri and Ghanta (2008) fits existing experimental data using artificial intelligence. The Delft Head Loss & Limit Deposit Velocity Framework provided by Miedema (2015), 2016a, 2016b explains the mechanism of pressure drop. It is considerably simple and has widespread applicability owing to the use of easy sampling parameters. Starting from the earliest empirical formula based on purely dimensionless analysis to the lift theory, energy theory, and two-phase flow theory, work is being performed related to theoretical analysis. However, microscopic parameters such as turbulent dissipation force, particle collision force, and momentum exchange have not yet been investigated.

Numerous scholars have made significant contributions to the study of concentration distribution; for example, Karabelas (1977), Roco and Shook (2010), Kaushal and Tomita (2002), and Gillies et al. (2004). They have performed several experimental studies for different operating conditions such as different diameters and particle sizes in different flow conditions. Miedima (2017) and others have developed methods of calculating the solid concentration profile in the vertical direction in pipelines based on previous experimental data with flow parameters such as eddy diffusivity and particle settling velocity. These methods can predict a close representation of the concentration distribution in varying degrees; however, they involve less flow parameters and more empirical coefficients, and their range of application and calculation accuracy relies on the experience of a reckoner. Kaushal and Tomita (2007) carried out experiments on particles with a narrow gradation (particle diameter: 0.125 mm and 0.44 mm). Experimental results clearly showed that the maximum concentrations of coarse particles occur in the zone that is approximately 0.2*D* (where *D* is the diameter of the pipe) from the wall, rather at than the bottom of the pipe. This proved the speculation by Wilson and Sellgren (2003) about the effect of near-wall lift on the particle concentration close to the bottom of a pipe. However, there is no mathematical model to predict and interpret this conclusion (Kaushal et al., 2012). Additionally, Kaushal et al. (2005) carried out experiments on a mixture of glass beads of two sizes (0.125 mm and 0.44 mm, equal fractions by mass) in a horizontal pipe with a diameter of 54.9 mm and analyzed the effect of particle size distribution on the pressure drop and concentration profile in pipelines.

In the field of numerical simulation, Ling et al. (2003), Kaushal et al. (2012), Gopaliya and Kaushal (2015, 2016), and Kumar et al. (2016) numerically simulated single-sized slurry flow through horizontal pipe under a wide range of operating conditions using the single-solid-phase Eulerian model in Fluent. Ekambara et al. (2009) predicted the behavior of horizontal solid–liquid pipeline flows under different conditions using the two-fluid model in ANSYS-CFX. Messa et al., 2014, Messa and Malavasi, 2015 proposed a two-fluid model and used it to simulate fully-suspended liquid–solid slurry flow in horizontal pipes using the PHOENICS software. Then, an improved wall function was developed, which clearly enhanced computing speed and accuracy. All these models can correctly predict flow characteristics to different degrees; however, they cannot accurately calculate the particle concentration distribution close to the wall, particularly for coarse particles. Chen et al. (2009) considered the coal particles with bimodal distribution as two solid-phase components and used the Eulerian multiphase model in Fluent to investigate the effects of influx velocity, total influx concentration, and grain composition on slurry flow characteristics such as constituent particle concentration distribution, velocity distribution, and pressure gradients. They found that the pressure drop observed in the simulation results of the double-solid-phase model is closer to experimental data, as compared to the results of the single-solid-phase model. In addition, Kaushal et al. (2017) used the Eulerian two-phase model in Fluent to simulate the pressure drop and particle concentration distribution in the flow of bimodal slurry comprising silica sand and fly ash at different ratios in a horizontal bend and obtained the variation in bend loss coefficient with increase in the percentage of fly ash. However, the bimodal slurry used in the abovementioned papers contains a large number of other-sized particles, and the generality of the model and the simulation accuracy of different-sized particle characteristics in slurry are limited.

In addition, even though the existing formula for horizontal pipes can predict slurry characteristics in various operating conditions such as friction resistance and solid concentration, it cannot be applied to complex geometries such as loop lines and gate valves because the empirical formula cannot consider slurry turbulence intensity, particle collision, energy exchange, etc. However, in practice, all pipeline systems in the dredging, mining, coal industries inevitably contain pumps, angular pipes, pipe branches, and other complex geometries. Thus, the formula fails to describe the properties of the entire system. Therefore, the development of a universal model is the goal of scholars worldwide.

For overcoming the abovementioned limitations, an integrated model based on the granular kinetic theory is developed using Fluent. This model can accurately describe the dynamic characteristics of pipeline slurry transport.