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Numerical Investigation of the Fluid Mixture Velocity on Critical Sand Settling Velocity in Multiphase Fluid Flow in Horizontal Pipes

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Abstract

Flow assurance studies are conducted to model the effective production and transportation of unprocessed multiphase reservoir fluids from the wellhead to the processing facilities through the pipeline systems. However, flow assurance challenges may occur due to the presence of sand particles in the fluids that are transported especially when producing from low strength sandstones reservoirs. There are also the complexities associated with changing nature of multiphase flow in pipelines, which may result in the manifestation of a number of transient flow patterns depending on the fluid properties, flow rates, pressure drop and pipe orientations. However, some of these challenges may occur which interrupt effective pipeline transportation of unprocessed multiphase fluids. In order to avoid these challenges and ensure continuous or unhindered flow, effective management of the complexity of the transient nature of the fluids was adopted. This study presents a numerical approach to investigate fluid mixture velocity on sand transport velocity under key flow patterns such as dispersed bubble, slug, and stratified flows in multiphase fluids. To achieve this, an automated system was developed from the mathematical expression using Python 3.10, Odeint (ordinary differential equation integrator) which uses the LSODA (Livermore Solver for Differential Equation Algorithm) to solve the complex differential equation for particle transport in multiphase flow. The effects of the fluid mixture velocity on the particle-fluid flow characteristics such as critical sand settling velocity has been numerically investigated the results showed that the critical sand settling velocity is greatly influenced by the fluid mixture velocity as well as the flow patterns. It was also observed that the in-situ position of the flow patterns; stratified, slug, and dispersed bubble flows based on the sand carrying capacity did not change as it was previously reported in the literature. Most of the investigations conducted in the literature on particle transport models for gas-liquid multiphase flow were developed based on experimental approaches with numerous limitations.

1.0 Introduction

With the advent of sand management in the oil and gas industry as an approach to curb the catastrophe event of a partial or complete blockage in pipelines with sand deposits, the evaluations of the number of phases of the fluid in pipelines became pertinent, hence, one of the factors that affects the transportation of gas-liquid-sand in pipes. Most research works have been conducted on a single and two-phase flow in pipes by numerous authors while little attention had been channeled towards three-phase or multiphase flow which is a typical flow system in oil and gas pipelines. However, this aspect of oil and gas production and transportation has received limited attentions in literature in the last years [1] [6]. The multiphase flow is defined as the mixture of two or more distinct phases (such as oil, water, gas and solids) flowing through a closed conduit. The behavior of a multiphase flow is much more complex compared to a single-phase flow. In addition, different phases normally do not travel at the same velocities. The difference in the situ average velocities among different phases results in a very important phenomena, which is the "slip" of one phase relative to others. However, the movement of liquid (water and oil) and gas in a pipeline or export pipeline at the same time results in different flow patterns in the flow system. The higher the number of phases, the higher the complexities they posed to the flow of fluids in the pipeline system. Furthermore, the velocity of the different phases in the system also determines how complex the flow system will be. The traveling velocity of the fluids is determined by the flow rates, fluids properties (viscosity, density and surface tension), and the pressure profiles. The continuous changing in flow patterns introduces additional complexities, which dependents on gas and liquid flow rates. [8] However, one of the major complexities that the flow pattern has is the transition region or the changes that occur as the boundary is approached. The flow becomes unstable as the boundary is reached and the growth of this instability causes transition from one flow pattern to another. Like the laminar-to-turbulent transition in single phase flow. These multiphase transitions can be rather unpredictable since they may depend on otherwise minor features of the flow, such as the roughness of the walls or the entrance conditions. Hence, the flow pattern boundaries are not distinctive lines but more poorly defined transition zones. The concept of flow patterns in pipes introduces new challenges in the understanding of multiphase fluids principally given the form in which fluids exist in pipes [5]. Again, the complexity of multiphase flows in pipelines is experienced with the presence of solid particles given that the interactions between the particles and the fluid that is being transported as shown in Figure 1.

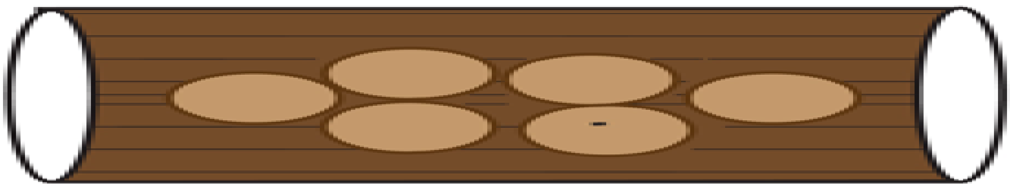

Figure 1: Fluid-Particle Interactions in Multiphase Pipeline

This study presents the numerical investigation of the effect of various fluid mixture velocities on solid-particle transport velocity under the operating conditions of the three key flow patterns; stratified flow, slug flow and dispersed bubble flow given that in the time past, many researchers had conducted numerous investigations on the effect of superficial liquid or gas velocity on particle transport, which is a hypothetical velocity using an experimental approach which lacks details and critical information which can be captured by numerical approach. More also, little or no investigation has been conducted on the effect of fluid mixture velocity on solid-particle transport velocity in pipes which represents the typical or real nature of fluid flow system in petroleum production pipelines.

1.1. Gas-Liquid-Solid Multiphase Flow

A couple of studies have been carried out for this type of phase-flow for modeling solid transport in pipes. [2] conducted the first experimental study about solids transport with gas-liquid mixtures in horizontal pipes. They investigated the effects of the solid concentration and pipe diameter on the saltation velocity for liquid–solid, bubble, plug, and slug flow regimes. They defined saltation velocity as the velocity needed to keep the solid particles barely skimming along the low side of the pipeline. Their experimental results were in good agreement with [3] correlation. However, [4] investigated the influence of gas fraction for high sand concentration and formulated a model based on experimental data. He discovered that the transition from moving bed to suspension takes place at higher superficial velocities than the transition velocity from the stratified wavy flow to slug flow and concluded that gas-liquid flow regime has no direct influence on the sand transport mode. Also, the effect of liquid viscosity and particle size on the sand transport is limited while the gas fraction influenced greatly the sand transport. [12] introduced a model very similar to the [4] correlation to describe solid transport in multiphase systems. Three-phase air-water-sand and air-oil-sand were used for experimental tests in a horizontal line. He discovered that the gas injection had a little effect on the sand transport when the flow is laminar and much influence for turbulent flow. [13] proposed a correlation for predicting the critical deposition velocity for three-phase flow. He developed a correlation applicable for low sand concentration by combining a modified [14], [15], and [13] correlations. [16] developed a model to investigate gas-liquid-solid intermittent and stratified flow patterns in horizontal and near horizontal pipes with low sand concentrations. This model over-predicted the sand particle velocity when compared to the experimental sand particle velocity in slug flow. [17] carried out numerous experimental tests with different gas and liquid fluids. He discovered that gas fractions have no direct impact on the critical slip velocity between sand and the carrier liquid, while the sand bed formation is strongly dependent on the inclination angle. [17] also applied OLGA code to predict the sand hold-up along the line and he obtained good fit data for both liquid–solid and gas-liquid-solid experiments. [18] presented a mathematical correlation and a computational algorithm to determine optimal transport velocity, particle velocity, particle hold-up and critical velocity in three-phase flow. However, the correlation exhibited good agreement with the experimental data. [19] experimentally investigated air-water-particle slug flow inside a horizontal pipeline for high sand concentrations. However, results showed that the gas ratio does not affect sand particle velocity. However, slug flow significantly influences sand particle mobility. [20] investigated the effect of the pipe inclination on the critical sand velocity. Although, minimum sand transport velocity is affected little by inclination in water-sand flow for two-phase flow. For three-phase flow, the pipe inclination modifies the gas-liquid flow regime and consequently the sand-transport mechanism. The developed model, based on [15] correlation for two-phase flow and [13] correlation for three-phase flow, shown a good agreement with literature data, especially for a pipe diameter of 0.1m. [1] analyzed sand particles flow regime in air-water stratified flow in horizontal pipelines for various sand concentrations. [21] carried out an experimental investigation of the minimum transport velocity (MTV) in both two-phase water-sand and three-phase air-water-sand flow. They discovered that MTV is greatly affected by the flow patterns and slug flow gives the best solid carrying capacity in pipe. Also, minimum transport velocity is strongly dependent on pipe orientations. [22] Performed preliminary experimental study of three-phase flows (air-water sand) in a horizontal pipe and was applied to develop sand liquid models present in literature. Pertinent observations were made during the experimental study from which numerous inferences were drawn. It was physically observed that different sand flow regimes were established from the data analysis. The sand flow regimes are; fully dispersed sand, moving dunes and stationary bed. However, the critical deposition velocities were predicted at different sand concentrations. It was concluded that sand transport characteristics and the critical sand deposition velocity are strongly dependent on gas-liquid flow regime and sand concentration.

From the literature above, it is observed that experimental approach was mainly predominant, and this approach cannot absolutely account for the hydrodynamic forces of interactions between the multiphase fluids and the entrained sand particles. Therefore, numerical approach was adopted for this study due to the provision of critical information such as multi-dimensional distribution of phases, dynamic flow regime transition and turbulent effects.

2.0 Methodology

2.1. Description of Numerical Approach for Particle Transport Prediction

The main objective of this research work is to use the developed numerical solution (Odeint) to simulate the effect of various fluid mixture velocities on the theorical developed particle transport equation as presented in equation (5). The Python 3.10, Odeint (ordinary differential equation integrator), which uses the LSODA (Livermore Solver for Differential Equation Algorithm) was utilized to solve the equation (5). To achieve this, all the equations were implemented in Python 3.10 to obtain dependent variable V_p (particle velocity) for predicting local and axial distribution of critical sand settling velocity, across the following flow regime: stratified, slug and dispersed bubble flow. Unlike the conventional 4^{th} order Runge Kutta explicit method adopted to solve non-linear differential equation in literature. However, the “Scipy. Integrate. Odeint” python solver utilizes adaptive step size to automatically reduce the computational error by less than the defined threshold implemented error tolerance value. Thus, the odeint solver estimates the integration error by comparing the results of two integrators which is intertwined to solve runtime.
The LSODA utilizes bounded Jacobian method and automatically selects between non-stiff (Adams Bash forth) and stiff (Backward differential formular (BDF) i.e., finite difference series). They are both explicit and implicit method respectively. Thus, if the errors are too large computationally, a warning message is displayed on the screen (above $1.1e^{-2}$) [23]. Python modules that are utilized include Scipy, Numpy and matplotlib. Pycharm integrated development environment was utilized to develop the algorithm for the program.

2.2. Development of Solid Particles Transport Model in Multiphase Flow System

The gas, liquid, and solid multiphase flow system was taken into account in a horizontal pipe flow system in Figure 2 when creating a solid-particle transport model. The governing equation for the solid-particle transport model in multiphase pipe flow system was modeled using two fundamental equations, continuity and momentum equations, as shown in equations 1 and 2 as shown below: After the application of the two fundamental equations used in modeling in fluid mechanics, equation (3) which is based on force balance was formulated. Different empirical correlations from the literature were substituted into each force in the force system as shown in equation (4) and the governing equation in equation (5) was developed.

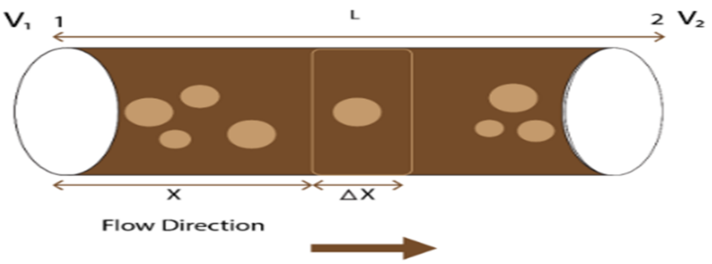

Figure 2: Pictorial View of Multiphase Fluids Flow in a Horizontal Pipeline

$$\frac{\partial(\ell_P)}{\partial t} + \frac{\partial(\ell_P v^P)}{\partial x} = 0 \quad (1)$$

$$\frac{\partial\left(\ell_P v^P\right)}{\partial t}+\frac{\partial\left(\ell_P\left(v^P\right)^2\right)}{\partial x}=\sum_{i=1}^{n}F_i^v \qquad (2)$$

$$M^p\frac{dV^p}{dt}=F_I^p+F_p^p+F_T^p+F_G^p+F_B^P+F_L^P+F_w^p+F_V^p+\sigma \qquad (3)$$

$$M^p\frac{dv^p}{dt}=C_D^p\rho_m\frac{\pi(d_p)^2}{4}\frac{(V_m-V_p)^2}{2}+\frac{\pi(d_p)^2\dot{m}_p}{4\quad A}(V_m-V_p)+\rho_L\frac{\pi}{4}(d_p)^2(V^i)^2-$$

$$\frac{\pi}{6}(d_p)^3\rho_p g\delta+\frac{\pi}{6}(d_p)^3\rho_m g\delta+\frac{1}{2}C_L^p\rho_m V_m^2 A+\frac{F_t}{L_t} \qquad (4)$$

$$\frac{dV^p}{dx}=\alpha V^p+\frac{\beta}{V^p}+\gamma \qquad (5)$$

The non-linear first order differential equation in equation (5) for particle transport velocity in gas-liquid multiphase flow in horizonal pipes developed analytically was resolved using numerical approach as described above. This equation enables critical sand settling velocity to be predicted in multiphase fluids in horizontal pipes.

3.0 Results and Discussion

The study shows the simulated effect of fluid mixture velocities on the developed solid-particle transport model in horizontal pipes in order to predict the flow characteristics such as critical sand settling velocity as a function of pipe length under the influence of the three key flow patterns; stratified, slug, and dispersed bubble flow in gas-liquid multiphase flow in pipes. Table 1 shows the input parameters that were used for the simulations. The simulations were conducted for a 6.5m pipe length, 0.5m pipe diameter, 0.2, 0.4, 0.8 m/s and 1.0, 2.0, 4.0 m/s fluid mixture velocities and 320um particle diameter of spherical shape of density of 2600kg/m^3.

Table 1: Input parameters for the developed numerical program

S/N	Parameter	Range	Unit
1	Fluid mixture velocity	(0.2, 0.4, 0.8) and (1.0, 2.0, 4.0)	m/s
2	Pipe length	6.5	m
3	Pipe diameter	0.5	m
4	Particle diameter	320	µm

3.1 Effect of Fluid Mixture Velocity Variation on Critical velocity Profiles in Gas-Liquid Multiphase Flow in Pipes

The effect(s) of fluid mixture velocity on the critical velocity profiles under the stratified flow conditions as observed in Figure 2 and 3 shows significant changes. As the pipe length increases, critical settling velocity decreases across the pipes. However, the magnitude of the critical velocity profiles for Figure 2 is larger i.e., solids are allowed to remain in suspension for a longer time when compared to Figure 3 despite the increase in the fluid mixture velocity. Again, under the slug flow operating conditions as observed in Figure 4, the critical velocity profile decreases across the pipe also due to the continuous reduction in the motion of fluid as it tends towards the exit point of the pipe due to gravity and frictional effects on the particles and the fluid itself. More also, the magnitude of the critical velocity profile is larger when compared to Figure 5 due to the increase in the fluid mixture velocity. Again, under dispersed bubble flow as observed in Figure 6, the critical velocity profile is larger in magnitude when compared to Figure 7 due to the reduction of fluid mixture velocity. Thus, a higher critical velocity depends on the maintained low fluid mixture velocity and flow patterns. According to [21, 22], critical velocity decreases whenever the slurry velocity is increased for multiphase flow system. Thus, the initial fluid mixture velocity is such that it should be maintained at reasonable low speed determined by Mach Number, within subsonic, sonic and supersonic flows.

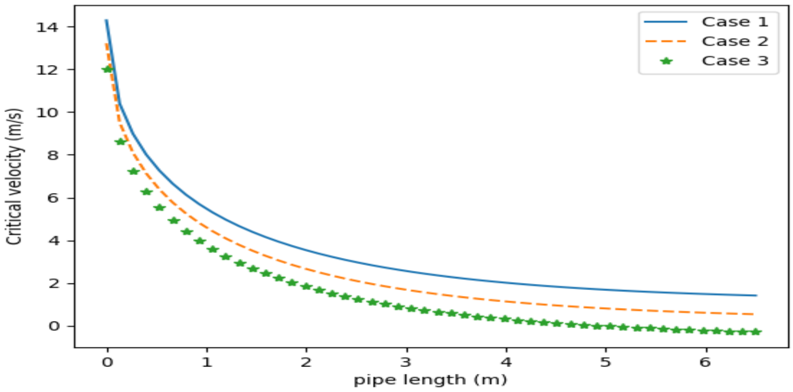

Figure 2: Critical velocity profile as a function of pipe length with fluid mixture velocity (0.2m/s, 0.4m/s, 0.8m/s) d_p=320 μm, and p_d = 0.5m for stratified flow operating conditions

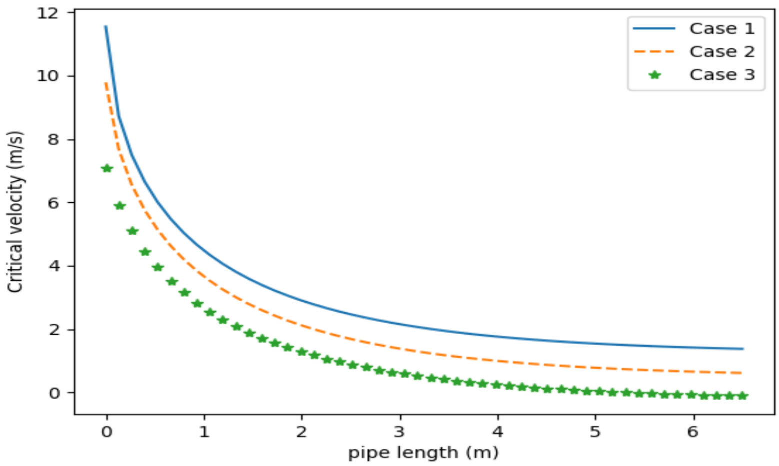

Figure 3: Critical velocity profile as a function of pipe length with fluid mixture velocity (1.0m/s, 2m/s, 4.m/s) d_p=320 μm, and p_d = 0.5m for stratified flow operating conditions

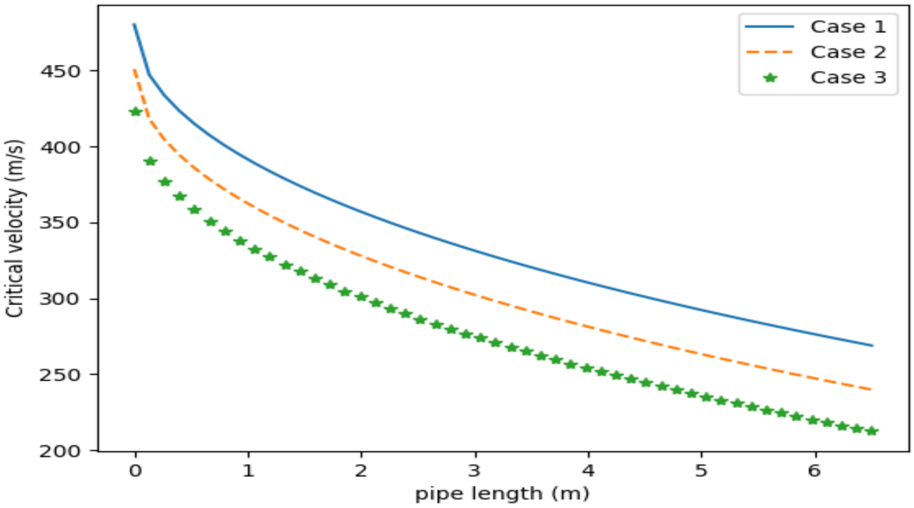

Figure 4: Critical velocity profile as a function of pipe length with fluid mixture velocity 0.2m/s, 0.4m/s, 0.8m/s) d_p=320 μm, and p_d = 0.5m for slug flow operating conditions.

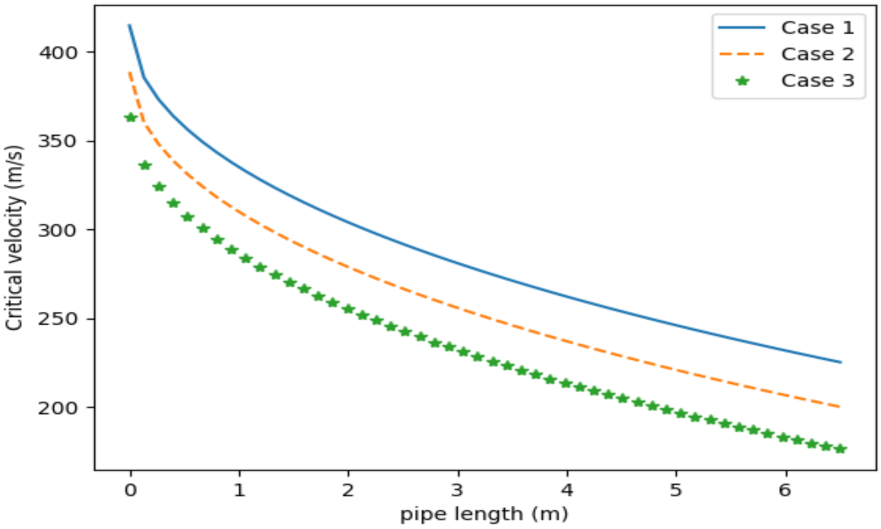

Figure 5: Critical velocity profile as a function of pipe length with fluid mixture velocity 1.0m/s, 2m/s, 4m/s) d_p=320 μm, and p_d = 0.5m for slug flow operating conditions

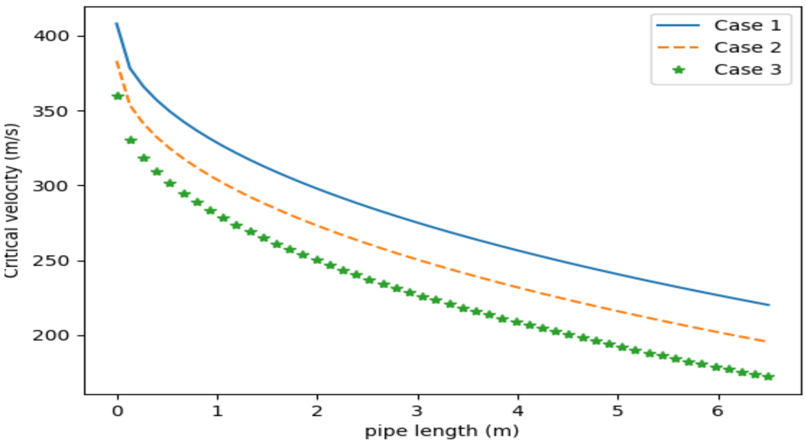

Figure 6: Critical velocity profile as a function of pipe length with fluid mixture velocity 0.2m/s, 0.4m/s, 0.8m/s) d_p=320 μm, and p_d = 0.5m for dispersed bubble flow operating condition

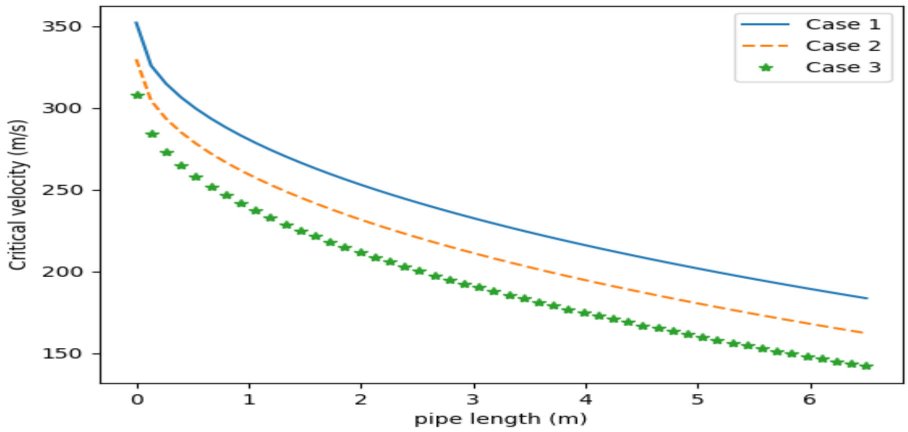

Figure 7: Critical velocity profile as a function of pipe length with fluid mixture velocity 1.0m/s, 2m/s, 4m/s) d_p=320 μm, and p_d = 0.5m for dispersed bubble flow operating conditions

5.2 Effects of Fluid Mixture Velocity Variation on Critical Sand Settling Velocity Profiles Under the Influence of the Three Key Flow Patterns in Pipes

The effect of the fluid mixture velocity variations on the critical velocity profiles shows significant changes as observed in Figures 8 and 9 as follows. This was greatly influenced by the combined flow patterns; stratified, slug, and dispersed bubble flows when compared to when the sand particles are not under the influence of the gas-liquid flow patterns. Hence, the changes in the velocities of the fluid flow depend on the three flow patterns and consequently on the variations of fluid mixture velocities. The increase in fluid mixture velocities reduces the magnitude of the velocity profiles as observed in Figure 9. According to [22], in all cases where the slurry velocity decreases, the critical deposition velocity is higher than the cases with an increasing velocity. The impact of this increasing velocity causes the solids to settle faster. It can be observed from the two graphs that slug and dispersed bubble flows have the highest influence on the carrying capacity of the fluid mixture. No significant influence on the carrying capacity of the fluid mixture under the stratified flow given that it allows settling of solids faster than expected.

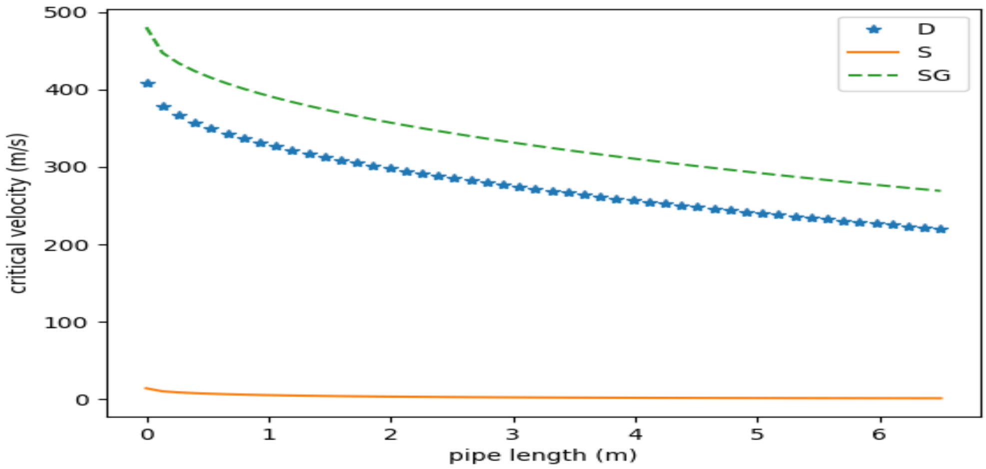

Figure 8: Critical velocity profiles as a function of pipe length reflecting the effect of the three flow patterns: stratified, slug and dispersed bubble flow with three cases of initial fluid mixture velocity (0.2m/s 0.4m/s 0.8m/s), d_p=320 μm and p_d = 0.5m

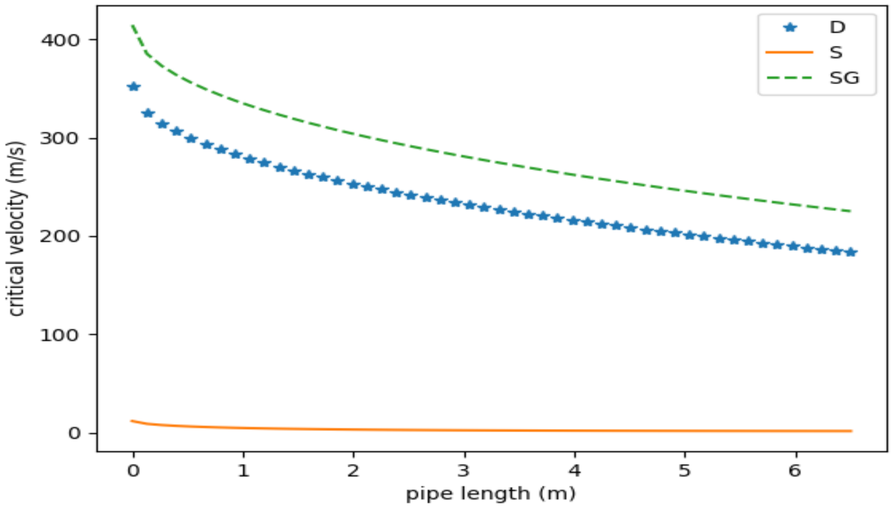

Figure 9: Critical velocity profiles as a function of pipe length reflecting the effect of the three flow patterns: stratified, slug and dispersed bubble flow with three cases of initial fluid mixture velocity (1.0m/s 2.0m/s 4.0m/s), d_p=320 μm and p_d = 0.5m

4.0 Conclusion

The effects of the fluid mixture velocity on the particle-fluid flow characteristics such as critical sand settling velocity has been numerically investigated under three key flow patterns; stratified, slug, and dispersed bubble flows in gas-liquid multiphase flow in horizontal pipes. The results showed that the critical sand settling velocity is greatly influenced by the fluid mixture velocity as well as the flow patterns. It was also observed that the in-situ position of the flow patterns; stratified, slug, and dispersed bubble flows based on the sand carrying capacity did not change as it was previously reported in the literature.

Nomenclature

V^p = Particle Velocity

x = Length of pipe

d_p = Particle Diameter

P_d = Pipe Diameter

α, β, γ = Constant Coefficient

F_I^P =Interfacial drag force exerted by liquid Mixture in multiphase flow.

F_B^P = force of buoyancy on the solid particle.

F_G^P = force of gravity on the solid particle.

F_P^P = force of particle-particle collision.

F_W^P =Frictional force from pipe-wall-particle interaction.

F_T^P =Turbulent (particle-liquid interaction) dispersive force.

F_L^P = Lift force.

F_V^P = Virtual mass force caused by the multiphase flow's acceleration.

σ= Surface tension exists between the gas-liquid interface and the solid particle.

M^p = Mass of the solid-particle

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Appendix

Flow Chart for Numerical Solutions for Solid-Particle Transport Velocity Model