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Experimental Characterization of the Influence of Particles similar to Gas Hydrates on the Slug Flow Pattern

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Abstract
The formation and agglomeration of gas hydrates represent a critical issue in flow assurance, as pipeline blockage is always a possibility. In order to manage this threat, one alternative is the use of anti-agglomerants (AA's), thus allowing the hydrates to form but avoiding their agglomeration. Although the AA's are widely used during the oil and gas production, the influence of the presence of hydrate particles on the hydrodynamics and structure of the slug flow – the prevailing flow pattern found in the oil and gas production – is still unknown. The goal of the present work is to analyze this influence. Experiments with polyethylene particles, in four different particle sizes (100 µm, 200 µm, 300 µm and 400 µm) and three volumetric concentrations (1%, 2.5% and 5%) were carried out. The test section consisted of a 26-mm ID, 9-m long horizontal pipe of Plexiglas. Resistivity sensors measured the main parameters of the slug flow, and High Speed Imaging was used to analyze the flow hydrodynamics and the particles' distribution. It was noticed that the liquid superficial velocity directly influences the particles' distribution, and, in addition, the particles influence the slug flow parameters.

Keywords
Slug flow pattern; transport of solids; flow with solid particles

Introduction
The spatial configurations assumed by the phases in a multiphase flow are known as flow patterns. In oil and gas production, slug flow is the prevailing flow regime, as dictated by the operational conditions. This flow pattern is characterized by the intermittent succession of structures called *unit cells*, composed of two distinct regions: the liquid slug and the elongated bubble, a bullet-shaped gas pocket that flows over a thin liquid film. The main parameters used to describe the slug flow pattern are the translational velocity of the elongated bubble, the lengths of the elongated bubble and slug regions and the slug frequency. The prediction of such parameters represents one of the challenges in the oil and gas industry.
The presence of solid particles such as sand, paraffins and hydrates poses yet another challenge for oil and gas production operations. Hydrates are crystals formed by cages of water molecules, which encapsulate a gas molecule. With the use of anti-agglomerant agents (AA's), those crystals flow as solid particles dispersed in the liquid phase. However, little is known about how the presence of these particles influences the slug flow structure.
Most studies in the literature assessing slug flow with solid particles analyze sand particles, studying mainly the particle transportability along the pipeline [1,2,3]. Rosas *et al.* [4], unlike previous works, seeks to evaluate the influence of solid particles on the slug flow structure. The authors analyzed 500-µm inert polyethylene particles, in volumetric concentrations under 1%. The present study extends the grid test of [4], using higher concentrations (up to 5%) and four different particle diameters (100 µm, 200 µm, 300 µm and 400 µm). The objective is to analyze not only the influence of the particles on the slug flow structure, but also if there are hydrodynamic factors that can generate agglomeration of the particles (in addition to the chemical forces, which will be partially eliminated by the presence of AA's).

Methodology
The experiments were conducted in a 9-m long, 26-mm ID flowloop made of transparent acrylic pipeline. The working fluids were air and water at ambient temperature and pressure. Polyethylene particles were chosen, due to their density similar to the hydrate particles (937 kg/m^3), in volumetric concentrations of 1%, 2.5% and 5%. Four different particle diameters were tested: 100 µm, 200 µm, 300 µm and 400 µm. Although the particles have hydrophobic surface characteristics, they were well mixed within the liquid phase during the experiments.
A total of twelve (12) combinations of liquid and gas flow rates were performed, all inside the slug flow pattern envelope. For the sake of comparisons, measurements for gas-liquid flows in the same

conditions and without the particles were carried out.

Figure 1 shows a scheme of the experimental flowloop. The liquid phase was stored in a tank, to which solid particles were added until the desired concentration was reached. The mixing was obtained through a mixing system, consisting of a funnel and a centrifugal pump connected by hoses. The funnel was used for sucking the particles that were deposited at the surface, while the centrifugal pump reinjected them at the bottom of the tank, generating a homogeneous dispersion. A helical pump displaced this slurry, while a compressor displaced the gas phase. Flow rates of both phases were measured by Coriolis flowmeters. Through a parallel plate mixer, the slurry and the gas were injected at the inlet of the test section as a stratified flow, which naturally transitioned to slug flow pattern a few meters downstream.

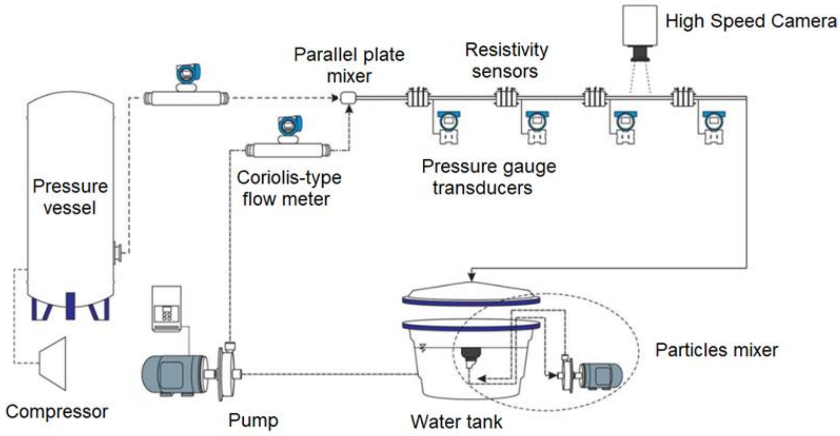

Figure 1. Experimental flowloop scheme.

Four measuring stations were arranged along the test section, each consisting of a pressure gauge and a pair of ring-shaped resistive sensors. After the test section, the phases were separated in a centrifugal separator. Table 1 presents the experimental flowloop characteristics and the range of parameters covered during the measurements.

A High Speed Camera was used to visualize the slug flow hydrodynamics and the slurry homogeneity, and resistive sensors were used to monitor the slug flow parameters. This type of sensor monitors the resistivity of the medium, in order to estimate the in-situ phase fraction. The sensors were used in pairs, allowing the estimation of the elongated bubble translational velocity.

Table 1. Experimental flowloop characteristics.

Fluids	Air and water
Particles density	937 kg/m^3
Particles diameters	100, 200, 300, 400 µm
Volumetric concentrations	1%, 2.5%, 5%
Pipeline wall material	Acrylic
Pipeline inclination	Horizontal
Pipeline ID/length	26 mm, 9 m
Measurement station positions	1.8, 3.7, 5.6, 7.5 m
Pressure and temperature	Ambient
Liquid superficial velocities	0.5 < JL < 1.5 m/s
Gas superficial velocities	0.25 < JG < 1.5 m/s
Mixture superficial velocities	1 < J < 3 m/s

Results and Discussion

From the images obtained during the experiments, it was observed that the slug flow directly influences the distribution of the particles along the unit cell. For cases with high liquid superficial velocities, the slurry remains homogeneous. In the case of low liquid superficial velocities, the turbulent diffusion is not high enough to keep the particles in suspension, so they tend to float close to the gas-liquid interface, causing a heterogeneous slurry along the unit cell. Figure 2 presents two distinct scenarios, with the same mixture velocity, but different liquid superficial velocities. It can be observed that, in the case with lowest liquid velocity (case b, JL = 0.5 m/s), the particles do not remain homogeneous as in the first one (case a). This trend is even stronger for larger particles, whereas the particles of 100 µm tend to remain homogeneous in both scenarios.

With the increase of the particles' concentration in the flow, there is the formation of a film around the elongated bubble, which becomes increasingly thicker with an increasing concentration of the particles, as shown in Fig. 3. This film influences the displacement of the elongated bubble, as well as the coalescence between elongated bubbles and dispersed bubbles along the flow.

The presence of the particles causes the amount of dispersed bubbles to decrease in both the film and the slug regions, especially when the particles are larger. This shows that the presence of the solid particles disturbs the detachment of dispersed bubbles from the elongated bubble tail. In turn, the presence of solid particles does not affect the elongated bubble profile significantly, as already noted [5].

It was also observed counterclockwise vortices at the elongated bubbles tails, as presented in Fig. 4. Although uncommon in the two-phase air-water slug flow, this type of vortices was also identified in previous works with particles [6], and very viscous slug flows [7], where they were named as "plunging jets". The presence of particles, which is more pronounced in the elongated bubble wake region (because of the capture of particles accumulated at the gas-liquid interface), increases the apparent viscosity of the liquid phase, thus contributing to the onset of this phenomenon, more frequent in viscous multiphase flows.

The present study, covering a wider range of particles diameters and concentrations, shows that the influence of the particles on the slug flow structure can be split into two different groups, according to the trends observed in the slug flow parameters. In the first group, the particles induced only slight changes, due to the turbulence modulation, caused by the particles presence. In the second group, the variations are significant, because of the particles influence in the slug flow formation.

The turbulence modulation theory [8] explains how the presence of solid particles interacts with the liquid velocity field. Large particles tend to create vortexes in their tails, thus promoting liquid turbulence. For small particles, the trend is the opposite. Therefore, for larger particles and higher concentrations, when the turbulence of the flow is promoted, it is assumed that the liquid velocity profile presents a flatter centerline. Since the liquid velocity ahead of the elongated bubble dictates the unit cell's translational velocity [9], then the flatter liquid velocity profile causes the bubble to decelerate. Again, for smaller particles and lower concentrations, the trend tends to be the opposite.

The variations in the elongated bubble velocity for the First Group are presented in Fig. 5. The results are expressed in terms of the percentage variation between the three-phase and the two-phase flow or, in other words, in terms of the percentage increase (or decrease) in the parameters, caused by the insertion of particles in the flow.

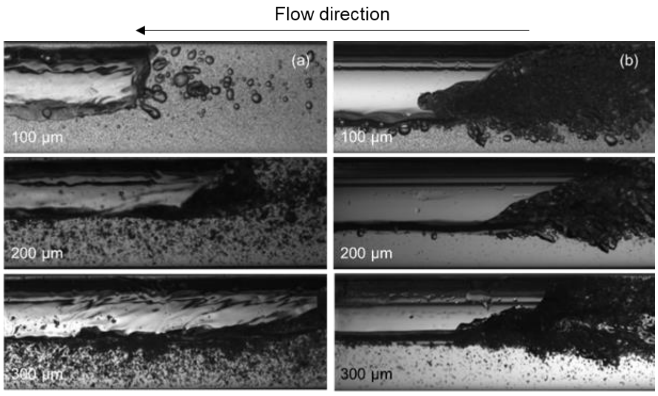

Figure 2. Wake region of the elongated bubble for 1% particle concentration and for different particle diameters (a) JL = 1.5 m/s and JG = 0.5 m/s and (b) JL = 0.5 m/s and JG = 1.5 m/s.

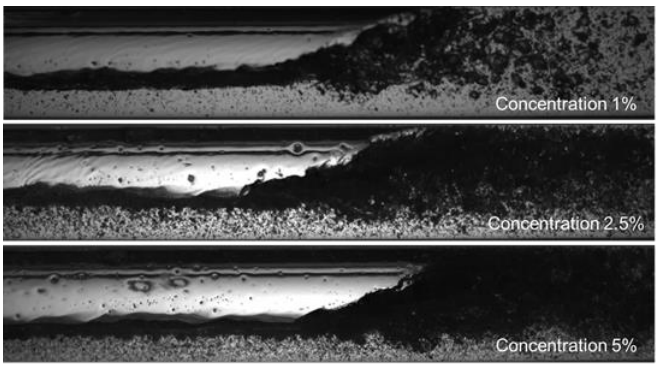

Figure 3. Wake region of the elongated bubble for different particle concentrations, JL = 1.0 m/s and JG = 1.0 m/s, particles of 200 µm.

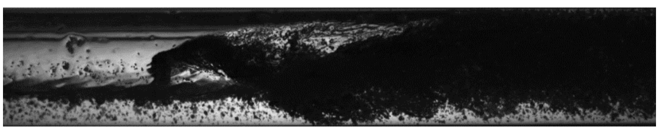

Figure 4. Plunging jet at the wake region of an elongated bubble, JL = 1.5 m/s and JG = 1.5 m/s, particles of 300 µm, 2.5% particle concentration.

As expected, because of the turbulence modulation, the elongated bubble velocity tends mostly to decrease for larger particles, while it tends to increase for the smaller diameters (100 µm and 200 µm). The trend with the particles concentration can also be observed: the lowest concentration (1%) tends mostly to increase the elongated bubble velocity (especially for smaller diameters), while higher concentrations (2.5% and 5%) tend mostly to decrease the elongated bubble velocity (even in the smaller diameters, like 200 µm). Owing to the variation in the elongated

bubble velocity, the unit cell undergoes a rearrangement, in order to balance the liquid and the gas mass distribution along the regions of the bubble and the slug. However, these variations are small, ranging between 30% and -30% for the elongated bubble and slug lengths, and also for the slug frequency.
For some particular combinations of liquid and gas flow rates (mainly for lower mixtures velocities and higher liquid loadings), it was noticed that the presence of the particles influenced the process of slug flow formation, and therefore they were separated in the Second Group.

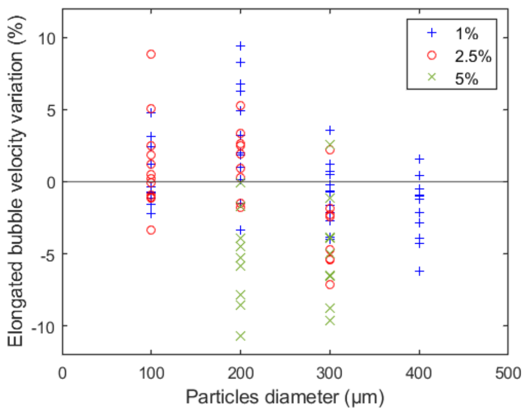

Figure 5. Variation of the elongated bubble velocity, with the insertion of particles, in the First Group.

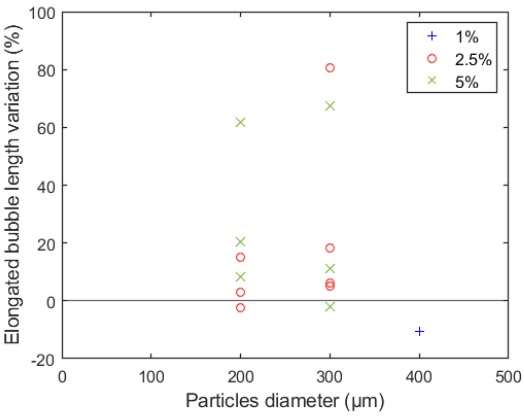

Figure 6. Variation of the elongated bubble length, with the insertion of particles, in the Second Group.

As the particles are most prone to dissipate the waves that form the slug regions, the unit cells formed in the Second Group are larger (have longer lengths) than the ones observed in the two-phase liquid-gas flow. This trend is in fact observed in the results, as shown in Fig. 6, for the elongated bubble length variation. The slug frequency, on the other hand, tends to decrease as the lengths increase, and so does the elongated bubble velocity.

Conclusions

The present study shows that the turbulence modulation, caused by the particles, acts towards the decrease of the elongated bubble velocity, because of the flatter liquid velocity profile. This effect is observed mostly for larger particles and higher concentrations. The elongated bubble and slug lengths remain approximately the same, when compared to the ones of the gas-liquid slug flow. They undergo slight changes only, because of the flatter velocity profile, what causes a rearrangement of the liquid in the unit cell.
However, for some particular scenarios, the particles influenced the process of slug flow formation, dissipating the waves that form the slug regions. In these cases, the unit cell evolves from higher lengths from the inlet of the test section.
The multiphase flow also influences the transport of the particles. It was observed that the homogeneous distribution is related to the liquid superficial velocity: if this latter is not high enough to promote the turbulent dispersion, it causes an accumulation of particles in the liquid-gas interface.

Acknowledgments

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Responsibility Notice

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References

[1] Oudeman, P. *SPE Production and Facilities*, 237–241, 1993.
[2] Goharzadeh, A.; Rodgers, P. *6th International Symposium on Measurement Techniques for Multiphase Flows*, Okinawa, Japan, 2009.
[3] Zerpa, L.; Rao, I.; Aman, Z.; Danielson, T.; Koh, C.; Sloan, E. D.; Sum, A. K. *Chemical Engineering Science* 99, 298–304, 2013
[4] Rosas, L.; Bassani, C.; Alves, R.; Schneider, F.; Marcelino, M.; Morales, R. E. M.; Sum, A. *AIChE Journal* 64, 2864–2880, 2018.
[5] Cavalli, S.; Alves, R. F.; Bassani, C.; Dos Santos, E. N.; Da Silva, M.; Marcelino, M.; Sum, A.; Morales, R. E. M. *6th Multiphase Flow Journeys*, Vitória, Brazil, 2021.
[6] Sassi, P.; Stiriba, Y.; Lobera, J.; Palero, V.; Pallarès, J. *Flow, Turbulence and Combustion* 105, 1035–1054, 2020.
[7] Kim, T.; Al-Safran, E.; Pereyra, E.; Sarica, C. *Journal of Petroleum Science and Engineering* 191, 107202, 2020.
[8] Gore, R. A.; Crowe, C. T. *International Journal of Multiphase Flow* 15, 279–285, 1989.
[9] Bendiksen, K. H. *Int. Journal of Multiphase Flow* 10, 467–483, 1984.