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Study of the Influence of Hydrate-Like Particles on Oil-Air Multiphase Flows

Vitor O. O. Machado[1], Paul A. D. Maldonado[1], João P. P. Siqueira[1], Paula S. Navarete[1], Guilherme de C. Mazur[1], Gianluca Lavalle[2], Eduardo N. dos Santos[1], Moisés A. Marcelino Neto[1], Amadeu K. Sum[3], Ana Cameirão[2], Annie Fidel-Dufour[4], Rigoberto E. M. Morales[1*]
[1]Multiphase Flow Research Center (NUEM), Federal University of Technology – Paraná (UTFPR), Brazil,
[2]Mines Saint-Etienne, Univ Lyon, CNRS, UMR 5307 LGF, Centre SPIN, Saint-Etienne, France
[3]Phases to Flow Laboratory, Colorado School of Mines, Golden, Colorado 80401, USA
[4]TotalEnergies, CSTJF – Pau, France
*rmorales@utfpr.edu.br

Abstract

Gas hydrates present a significant threat to flow assurance because of their rapid formation and potential to block pipes. One strategy for managing this issue involves the use of anti-agglomerants (AAs), which allow hydrate formation while preventing agglomeration and making the hydrate particles to flow within the liquid as a slurry. Despite the importance of this topic, there is scant literature available on the impact of these particles on key flow parameters such as pressure drop, liquid holdup and overall flow topology. The aim of this study is to address these gaps, with a special focus on the stratified and slug flow patterns. To achieve this goal, experiments were conducted using air and oil as working fluids, combined with model polyethylene particles having a density close to that of gas hydrates. These experiments were performed within a 50-mm inner diameter, 34-meter long test section flow loop. Four different particle concentrations were investigated: 0%, 5%, 10%, and 20% v/v in the liquid phase. Preliminary findings indicate that increasing particle concentration leads to a corresponding increase in pressure drop under both stratified and slug flow conditions. Additionally, the presence of particles significantly changes the flow topology, what becomes particularly as demonstrated by the early transition to slug flow from stratified flow.

Keywords

Hydrate-like particles; Multiphase-flow; Hydrate Management; Slug-Flow; Stratified-Flow.

Introduction

Most studies that investigate flow with solid particles have focused on the transportation of sand particles [1,2]. In this scenario, the solid-liquid density ratios are much higher than those in hydrate transportation, and the solid concentrations studied are usually much smaller (up to 2% v/v) than those of the present work.

A review of the literature demonstrates that there are few studies on multiphase flow with solid particles specifically addressing the influence of hydrate-like particles on such flows. Among the studies dedicated to this topic, slug flow has predominated, typically with water as the liquid phase.

One such study, conducted by Rosas et al. [3], used air-water and polyethylene particles (with a density of 938 kg/m^3 and approximately 500 µm in size) to examine the influence of hydrate-like particles on slug flow hydrodynamics.

Additionally, Sassi et al. [4,5] conducted experiments to assess the influence of solid particles on both the flow regime and the slug flow parameters. They also used air and water as the working fluids but used polypropylene particles, with a density of 866 kg/m^3 and with diameters ranging between 1 and 2 mm to simulate hydrates. Unlike these studies, where the particles are lighter than the liquid and thus naturally tend to buoy, the particles examined in this research are heavier than the liquid phase and may settle if the energy to keep them suspended is insufficient.

Furthermore, the study will also include testing under stratified flow conditions to comprehend the impact of varying solid concentrations on key flow parameters such as pressure drop, liquid holdup, and overall flow topology across a wider range of conditions.

Methodology

The measurements were conducted in a flow loop with a test section consisting of a 34-meter-long, 50-mm inner diameter horizontal pipeline made of transparent acrylic, enabling flow visualization using high-speed imaging techniques. Air and oil ($\rho_L = 770$ kg/m^3, $\mu_L = 2.5$ cP) were used as working fluids. The particles were made of polyethylene with a density of 930 kg/m^3, similar to that of gas hydrates and were polydisperse with a mean diameter of 208 µm. Volumetric concentrations of 5%, 10%, and 20% were used.

A total of thirty (30) combinations of liquid and gas flow rates were tested for the stratified flow pattern (0.5 < j_G < 5.5 m/s and 0.035 <$j_{L/SL}$ < 0.07 m/s), and fifteen (15) for the slug flow pattern (0.25 < j_G < 1.75 m/s and 0.25 < $j_{L/SL}$< 1.5 m/s). Measurements were conducted both with (5%, 10%, and 20% v/v) and without (0% v/v) particles, keeping identical gas and liquid/slurry flow rates for comparative analysis.

The test section was equipped with five different measuring stations located at distances of 2, 9, 16, 23 and 30 m from the inlet. Each station included a ring-shaped phase sensor developed in-house and a pressure transducer. Additionally, a differential pressure transducer was installed. A high-speed camera was positioned immediately after the fourth measuring station, and a PT100 sensor was used to measure temperature at that same station.

Results and Discussion

This topic will be split into two sections: the first section will report the stratified flow results, while the second section will cover the slug flow.

Stratified flow

In Fig. (1), the pressure drop without the presence of particles is compared to the ones with different particle concentrations.

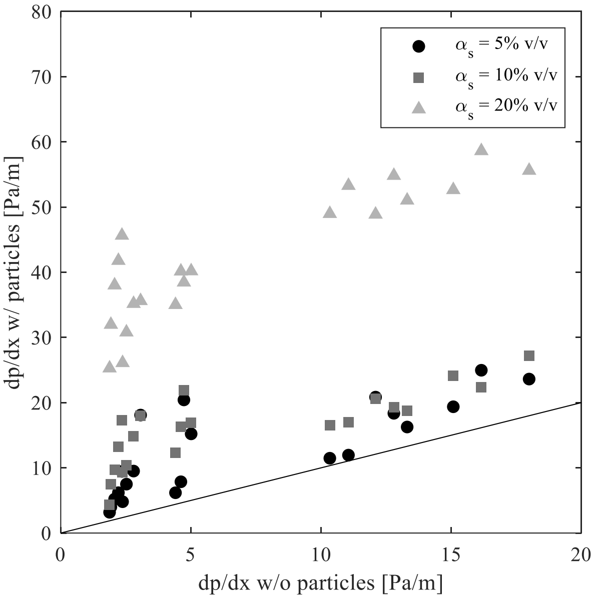

Figure 1. Comparison between the system pressure drop with different particle concentrations vs without particles.

As it can be seen, the presence of particles greatly increases the system pressure drop.

To understand this effect, the influence of 5% v/v of particles on the flow topology is shown in Fig. (2).

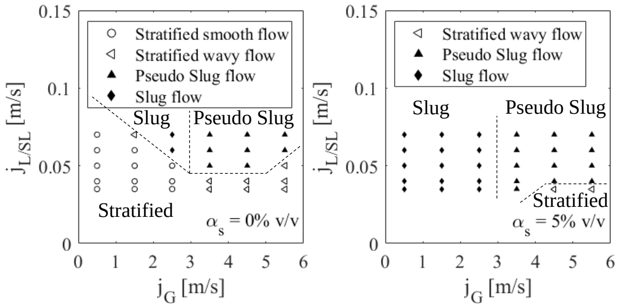

Figure 2. Flow maps showing the flow topology without particles (left) and with 5% v/v of particles (right)

The comparison between the system with 0% v/v and 5% v/v of particles shows an early transition to slug flow and an increase in the pseudo-slug region in the presence of particles.

This early flow destabilization is directly linked to particle transportation. Under stratified flow conditions, particularly at low gas superficial velocities, insufficient energy in the flow led to particle bedding. Consequently, particles began to accumulate, partially blocking the pipeline, as shown in Fig. (3).

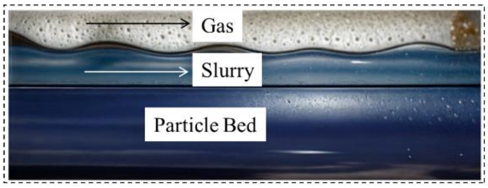

Figure 3. Partial blockage caused by the particle bedding on the bottom of the pipeline.

This increased the velocity of the phases and intensified the interaction between the gas and the slurry layer, promoting waves that eventually developed into slugs. The pressure drop time-series shown in Fig. (4) illustrates this transient phenomenon.

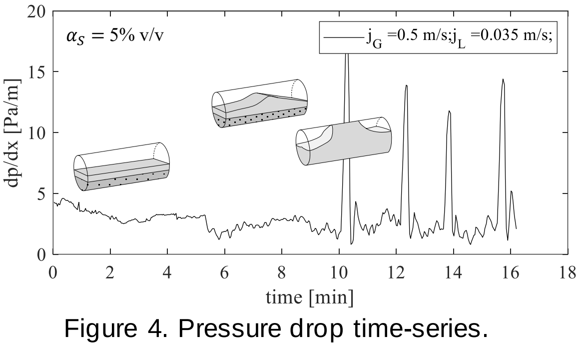

Figure 4. Pressure drop time-series.

At the beginning of the time-series, a well-behaved pressure drop signal is evident, associated with the solid bed accumulation on the bottom of the pipe. However, when a slug is formed, a peak in the pressure drop occurs, which is attributed to the cross-section blockage caused by the slurry-slug. This explains the significant increase in pressure drop with the presence of particles.

Additionally, the frequency of slug formation is noticeably low (approximately 1 slug per ~2

minutes), corresponding to the time required for the liquid level to recover after the passage of these slugs.
Image processing techniques were used to measure the front and tail velocity of the liquid slugs. Plotting the tail velocity (u_T) of these slugs versus the mixture velocity (j_{mix}) for a 5% v/v concentration along with the model of Grenier [6] (Fig. (5)), it is shown that although these slugs are formed under stratified flow conditions due to the partial blockage of the pipeline, their tail (bubble front) velocity can be accurately modeled as that of a regular slug flow.

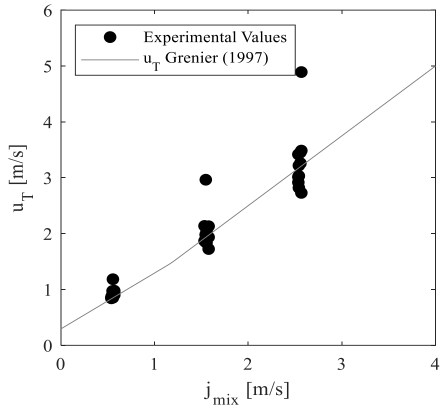

Figure 5. Slug tail velocity vs the model of Grenier [6].

The velocities extracted from the image processing were used to verify the stability of these slugs. According to Bendiksen [7] the slug stability criteria can be summarized as follows: a slug will be stable if its front velocity is greater than or equal to its tail velocity. By calculating the difference between the front and tail velocity of each structure it was observed that almost all the slugs remained stable even at 23 m from the inlet, as shown in Fig. (6).

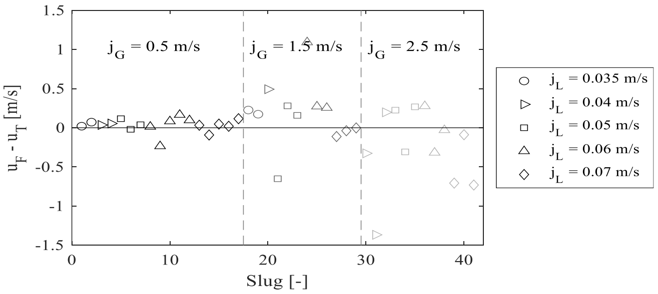

Figure 6. Evaluation of the slug stability by comparing its front (u_F) and tail (u_T) velocities according to the criteria of Bendiksen [7].

Therefore, although the solid particles were responsible for an early flow destabilization and the structures were formed under stratified flow conditions, their tail velocity behaves like that of a regular slug flow, and they remain stable throughout the pipeline.

Slug flow

In Figure (7), the experimental dimensionless pressure drop (Eq. (1)) is plotted against the Lockhart-Martinelli parameter (χ) (Eq. (2)) for every particle concentration studied.

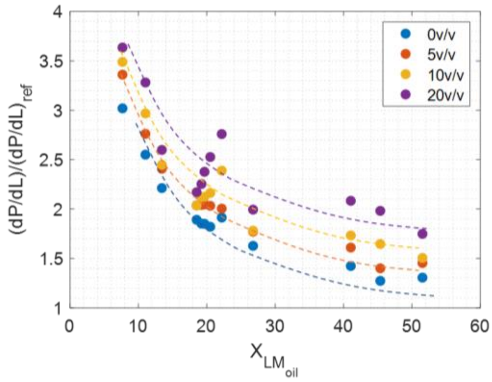

Figure 7. Pressure drop behavior with the Lockhart-Martinelli parameter.

$$\frac{dP}{dL}_{experimental} \Big/ \frac{dP}{dL}\Big|_{j_L}{}_{reference} \qquad (1)$$

$$\chi_{LM_{oil}} = \frac{dP}{dL}\Big|_{j_L}{}_{reference} \Big/ \frac{dP}{dL}\Big|_{j_G} \qquad (2)$$

The j_L and j_G pressure drops were estimated as if each phase were flowing alone in the pipeline, according to Taitel and Dukler [8]. Additionally, the reference values used to calculate the pressure drop for the liquid phase are based on the thermophysical properties of the oil whereas air, the gas phase, was assumed as an ideal gas.
Similarly to the trend observed under stratified flow conditions, the increase in particle concentration resulted in an increase in the pressure drop. However, differently than that what happens in stratified flow, in slug flow there was no significant particle settlement since turbulence was much higher. Therefore, the changes in pressure drop were associated with the particles changing the viscosity and the density of the slurry mixture.
The particles also influenced the organization of the slug flow unit cell. For example, for $j_G = j_L$ =1.5 m/s, it was observed that the particles affected the bubble length and slug regions, as illustrated in Fig. (8) by comparing the case without particles to the case with 5% v/v particle concentration. Along the test line, it is expected that the gas would expand because of the pressure drop, leading to an increase in the size of the liquid slug. If the liquid viscosity increases (by considering the effect of the increase in the apparent viscosity with the increase in particle concentration), the nose of the Taylor bubble might narrow, resulting in a longer length in this region. As the Taylor bubble length increases, it is expected that the liquid slug length would also increase, given the liquid slurry incompressibility.

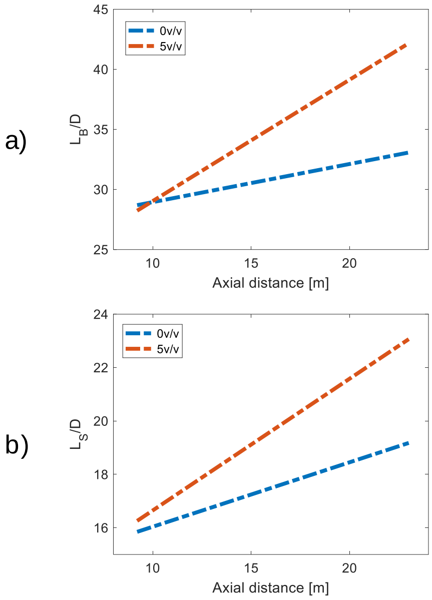

Figure 8. Mean values for Taylor bubble (a) and liquid slug (b) lengths along the test line for the cases without particles and with a 5% v/v particle concentration.

The particles also influenced the velocity of the Taylor bubble, as it can be seen in Fig. (9) for the cases without particles and with 5% v/v particles.

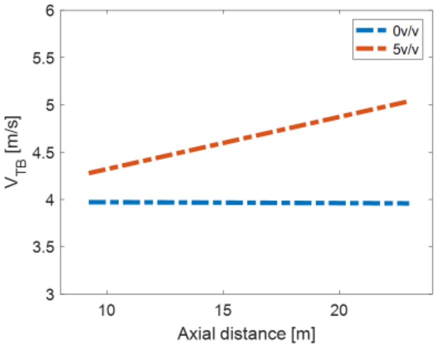

Figure 9. Mean values of the Taylor bubble velocity along the test line for the cases without particles and with a 5% v/v particle concentration.

The increase in velocity in the case with particles can be attributed to the fact that the viscosity of the slurry increases when particles are added to a liquid and a homogenized mixture is assumed. As a result, the velocity of the Taylor bubble also increases.

Conclusions

Particles significantly influenced the flow topology under stratified flow conditions, leading to an early transition to slug flow and an increase in the pseudo-slug region.

Although occurring in stratified flow conditions, these slug structures exhibited a tail velocity comparable to that of regular slugs and remained stable in the pipeline.

The transit of these slugs caused a peak in the pressure drop, thus resulting in an overall increase in the pressure loss along the pipe.

Additionally, the particles led to an increase in the slug flow pressure drop, but for different reasons nevertheless. Contrary to what happens in stratified flow conditions, the particles did not settle under slug flow conditions, and the increase in energy losses was attributed to changes in the slurry mixture properties.

Furthermore, it was observed that the particles affected the organization of the unit cell and the velocity of the Taylor bubble.

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Responsibility Notice

The authors are the only responsible for the paper content.

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