

COB-2023-1547

INFLUENCE OF HYDRATE-LIKE PARTICLES IN AIR-WATER GAS-LIQUID STRATIFIED FLOW PATTERN

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Abstract. Hydrate management is a strategy that can be used in deep-water oil exploration in which hydrates are allowed to form, but under control so that pipeline blockage is avoided. In this case, the formed hydrate particles are transported within the liquid phase, resulting in a slurry flow. In this sense, the impact of these solids on the flow hydrodynamics is of consider interest of the oil industry. Despite the importance of the topic, very little is known regarding hydrate particle transportation. In face of the exposed, the present work aims to understand the effect of the solid concentration in parameters such as the system pressure drop, the mean liquid level in the pipe and the flow configuration itself, under stratified flow condition. For that, air, water and polyethylene particles, which mimics the hydrates, were used as the working phases and put to flow in a loop which has a 34 m long, 50 mm of inner diameter test section. The main results show that particles have a minor impact on the liquid mean height while increasing the system pressure drop. Also, due to poor transportation capacity at low phases' superficial velocity, resulting in particle accumulation in the pipeline, intermittent transportation of solids by means of structures that resemble slugs prevailed at 10 and 20% v/v particle concentration.

Keywords: hydrates, gas-liquid-solid flow, stratified flow

1. INTRODUCTION

Stratified gas-liquid flow is a topological multiphase organization commonly found in various operations, such as in nuclear reactors, oil and gas pipelines, among others (de Sampaio et al., 2008). This pattern is characterized by the denser phase, the liquid, flowing at the bottom of the pipe, while the lighter phase, the gas, flows on the upper part of the cross-section. The interface between the two phases can be either smooth or covered by waves.

Not always the operation environment provides conditions that guarantee that only gas and liquid phases will be flowing in the pipeline. For instance, in oil and gas reservoirs, sand particles can be transported due to unconsolidated formation; in coalbed methane production wells, coal particles can be generated during the drilling process; and, in the case of interest of the present work, hydrate can form in offshore oil and gas exploration (Dabirian et al., 2015; Fajemidupe et al., 2019; Ravichandran and Daraboina, 2019; Wang et al., 2019; Song et al., 2020).

From the point of view of the flow assurance area, hydrates, especially in deep-water exploration – which provides a favorable condition for their formation – represent a serious threat to the operation (Koh et al., 2002). One of the strategies that can be used to deal with this problem is called hydrate management, in which hydrates are allowed to form, but under control, in order to prevent pipeline blockage. In this case, the hydrate particles are transported within the flow (Lv et al., 2013; Dapena et al., 2017).

Despite the importance of the topic, very little is known regarding hydrate solid transportation under gas-liquid stratified flow conditions, and how these particles affect the flow itself. In the literature, most of the works that investigated gas-liquid-solid stratified flow were concerned with the transport of sand particles (Dabirian et al., 2015; Padsalgikar et al., 2017; Fajemidupe et al., 2019). In this case the studied particle concentration is usually up to 2% v/v, which is lower than that expected for hydrate transportation, that can easily reach the 10% v/v mark, and the solid density is usually around $\rho_{sand} \sim 2500 \text{ kg/m}^3$, which is higher than that of hydrates, that can be less denser than the water $\rho_{hydrates} < 1000 \text{ kg/m}^3$ (Hu et al., 2022).

This distinct solids' density can lead to profound differences in the physics of the flow. Systems involving liquid-solid transportation are also separated in patterns, or transportation modes. For settling slurries, a common classification of the solid transportation was proposed by Doron and Barnea, (1996). If the flow velocity is high enough, turbulence is capable of dispersing the particles and a homogeneous solid distribution is achieved in the cross-section. By reducing the velocity, the particles start to sink and a heterogeneous distribution occurs, i.e. solids get more concentrated in the pipe bottom than in the upper part of the cross-section. Further decrement of the flow rate results in particle settlement, and they started to get transported as a moving bed of solids. Finally, if the velocity is low enough, particle transportation ceases and a stationary bed is formed.

Although this classification of the transportation modes was first described for settling solids in liquid-solid flow, it is also used to other scenarios as well, such as: in ice-slurry transportation, where solids are lighter than the carrier fluid, although, in this case, the particles float and the beds are seen in the upper part of the pipe cross-section (Kitanovski and Poredos, 2002; Kitanovski et al., 2005); gas-liquid-solid stratified flow with sinking particles such as sand (Ibarra, Mohan and Shoham, 2014; Dabirian et al. 2015); and gas-liquid-solid stratified flow with floating particles, such as cases where the density of hydrates is less than that of water, although in this scenario hydrates will float, instead of settling, and accumulate at the gas liquid interface, hence no static bed layer is expected (Hu et al., 2022).

Therefore, considering an air-water stratified flow as the reference system, if it contains solid as dense as sand, the particle settlement at low phase velocities can result in a large amount of energy loss due to the particle-particle and particle-wall interaction. On the other hand, if solids density is lower than the carrier liquid, it is expected that, at low flow velocity condition, the particles will concentrate at the interface, possibly altering its dynamics. Hence, the conclusions drawn by the many studies using sand probably not hold for the hydrate transportation scenario.

In the literature only few experimental investigation, such those performed by Cavalli, (2020) and Sassi et al., (2020), were done employing solids lighter than the liquid phase. Although, its noteworthy that in their case the flow pattern studied was slug flow, which dynamics is very different than that of stratified flow.

Therefore, the present experimental investigation was done in order to fill this gap found in the literature and provide useful information regarding the hydrodynamics of the hydrate transportation under stratified flow condition. In order to simulate this flow condition, air and water were used as working phases and polymeric particles, which mimic hydrate characteristics, were used as the solid phase. The objectives of this work are threefold: investigate how the particle volume fraction, i.e. volumetric concentration, affects the flow pattern itself; the system pressure drop and the average liquid level of the stratified flow.

2. EXPERIMENTAL FACILITY

The experimental facility used to study the transport of hydrate-like particles under stratified flow condition, is presented in Figure 1. It is separated in three distinct sections: the gas line, the slurry line and the test section. The gas line consists on a screw compressor (1); a pressure vessel (2), used to reduce the gas pressure fluctuations; and a Coriolis flow meter (3), which measures the gas mass flow rate. The slurry line is composed of: a slurry reservoir (4), which is equipped with a mixture system (5) designed to ensure particle homogeneity inside the tank; a centrifugal pump (6); and a Coriolis flow meter (7), which measures the slurry mass flow rate. The gas and slurry phases are mixed by means of a parallel plate (8). The test section is composed of 50 mm inner diameter transparent acrylic pipes, to allow flow visualization, which are assembled together to form a 34 meters long flow line.

The test section is equipped with five measuring stations (9) (MS) spaced 7 m apart and located at 2 m (40 D), 9 m (180 D), 16 m (320 D) and 23 m (460 D) and 30 m (600 D) from the inlet. Each measurement station has a manometric pressure transducer (P) which is used to calculate the local gas superficial velocity by considering air as an ideal gas. The fourth measuring station is also equipped with a PT100 sensor (T) for temperature monitoring. A high-speed camera (10), was positioned right after the fourth measuring station to record flow images, which were used to obtain the local liquid/slurry level in the pipeline. The pressure gradient was measured by a differential pressure sensor (11) located between the second and fourth measuring stations. At the outlet, a cylindrical cyclone separator (12) was used to separate the gas and slurry phases. It was design ensuring that the outlet of the flow-loop is never flooded, thus guaranteeing atmospheric pressure at it.

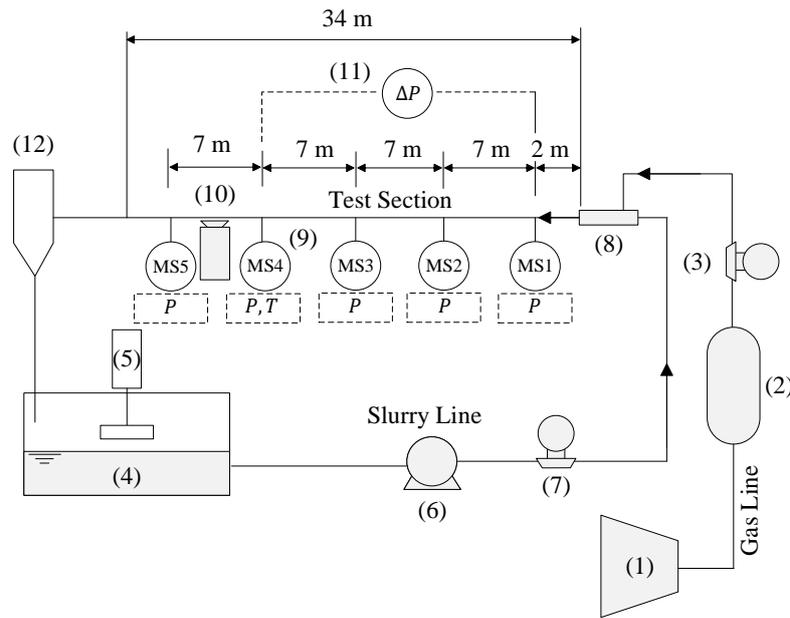


Figure 1. Experimental facility.

3. METHODOLOGY

As shown in the experimental facility schematics, the liquid-solid mixture with the desired particle concentration is prepared inside the slurry tank and are pumped through the slurry line to the test section inlet, where it gets mixed with air. For this methodology to work two conditions must be guaranteed:

- The mixture must remain as homogeneous as possible through the slurry line, since non-homogeneous distribution or the formation of solid beds may result in particle accumulation and partial blockage of the line, thus implying in a smaller particle concentration in the test section than that inserted in the slurry tank. Homogeneous slurry in the slurry line is guaranteed by using a smaller pipe diameter pipe on it, than that used in the test section, so that the velocity on this portion of the flow loop is always high in comparison to that of the test section.

- The mixture must be homogeneous inside the tank, so that the desired solid concentration is pumped. This is guaranteed by the mixing system coupled to the slurry tank. Although, the particles drawdown can be challenging when the solids have poor wettability, since, besides the gravitational force, the mixing system needs to overcome also the surface tension forces (Khazam and Kresta, 2008). Poor wettability may also impact directly on particle transportation, since more energy must be imparted to remove the particles from the gas-liquid interface.

Polyethylene is a hydrophobic material (Novak and Florián, 2001), hence the liquid in the two-phase gas-liquid reference system, i.e. 0% v/v of particles, could not be pure water, since it would result in poor mixing in the tank and in the loop. Therefore, an additive was needed to improve the solid wettability.

A full wet solid surface is achieved when the contact angle of a drop of liquid in its surface reaches the critical value of zero (Peker and Helvaci, 2008). In line with this, Zisman (1964) developed the concept of a critical liquid-gas surface tension (σ_{crit}), which is the lowest surface tension that a liquid must have to fully wet a solid surface. A surface tension higher than the critical one will result in partial wettability, or in the case in which the contact angle is higher than 90°, no wettability.

For polyethylene σ_{crit} is approximate 30 mN/m (Starkweather, 1965; Wu, 1968), which is lower than that of water. Hence, in this work, small quantities of commercial detergent were used to lower water surface tension and improve polyethylene wettability. The amount of detergent was determined empirically by evaluating qualitatively the relation between wettability improvement, which was desired, and formation of foam, which was undesired.

A volumetric fraction of detergent equal to $\alpha_D = 0.08\%$ v/v, calculated as shown in Eq.(1), where α_k is the volumetric fraction of a phase “k”, V_k its volume and V_M is the volume of the mixture, was found to be optimal since it improved greatly the solid mixing in water with minimum formation of foam, while retaining water original density and viscosity. Therefore, the working phases in the reference gas-liquid system consisted of air and a mixture of water and 0.08% v/v of detergent.

$$\alpha_k = V_k/V_M \quad (1)$$

Besides the case without particles, three particle concentration were investigated, 5, 10 and 20 %v/v. The volume of particle inserted on the tank on each condition was calculated through Eq.(1) and then converted to mass through the particle density.

Once the desired phase mixture was inside the tank, the experimental procedure consisted on: turning on the mixture system to ensure a homogeneous mixture on the tank. Then, a pair of phases superficial velocity (j_L for the liquid phase and j_G for the gas phase) that resulted in stratified flow was set. The conditions investigated in the present work, that ranged between $0.035 \text{ m/s} \leq j_L \leq 0.07 \text{ m/s}$ and $0.5 \text{ m/s} \leq j_G \leq 5.5 \text{ m/s}$, are shown in Figure 2 together with the theoretical stratified stability curve, calculated as the Viscous Kelvin Helmholtz criteria of Barnea and Taitel (1993) using air and water as working fluids. The superficial velocities marked in the flow map in Figure 2 were used throughout all the particle concentration studied (0 to 20% v/v), although, when there were solids on the tank, the superficial velocity of the liquid phase correspond to that of the mixture of water + particles, hence, being referred as the superficial velocity of the slurry (j_{SL}).

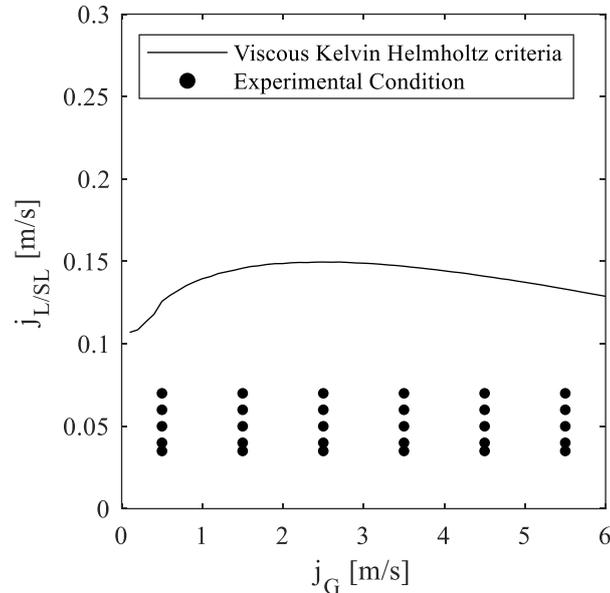


Figure 2. Flow map showing the investigated phases superficial velocity and the Viscous Kelvin Helmholtz criteria for air and water.

Once the phase velocities were set, using the high speed camera, a single frame of the flow was recorded every 2 minutes. These images were compared until no difference between the liquid level was found, thus indicating that a steady/stable flow was achieved. Then, differential pressure was recorded for 60 s while the flow images were recorded for 10s. After that, a new pair of phase velocity was set and the procedure was repeated.

The same experimental routine was used for every particle concentration studied.

4. INFLUENCE OF THE PARTICLE CONCENTRATION ON THE FLOW PATTERN

The influence of the particles on the flow pattern is presented on Figure 3.

For 5 % v/v of particles, no major differences in the flow pattern was seen for the superficial velocities investigated in the present work, i.e. the flow pattern was mainly regular stratified flow, with pseudo slug flow occurring at high gas and liquid superficial velocity. In terms of particle transportation mode, at smaller phase velocities, particles were more concentrated at the interface, while when the velocities were higher a homogeneous flow was achieved. This can be seen in Figure 4, where images of the flow behavior as a function of the phases' superficial velocity are shown.

As can be seen, by increasing either the gas or the liquid superficial velocity particles become more dispersed within the liquid layer. An increment on the liquid superficial velocity has a more obvious impact on increasing the liquid turbulence which is one of the main mechanisms responsible for particle dispersion. In turn, an increasing of gas superficial velocity, not only increment the liquid layer velocity, due to the increased drag exerted by it, but increase the interfacial turbulence, both helping in particle dispersion (Dabirian et al., 2015).

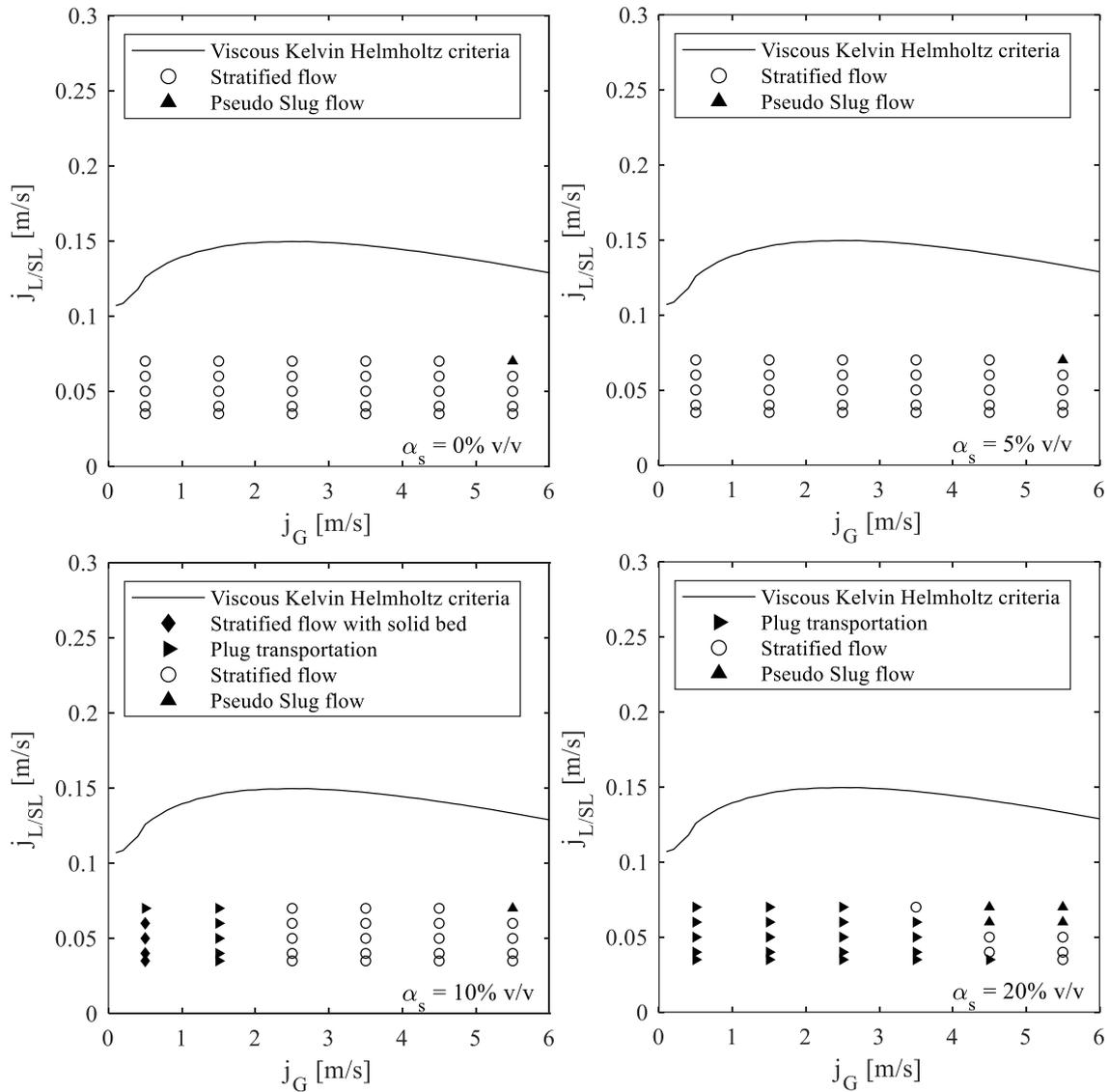


Figure 3. Flow map showing the changes in the flow pattern as a function of the particle concentration

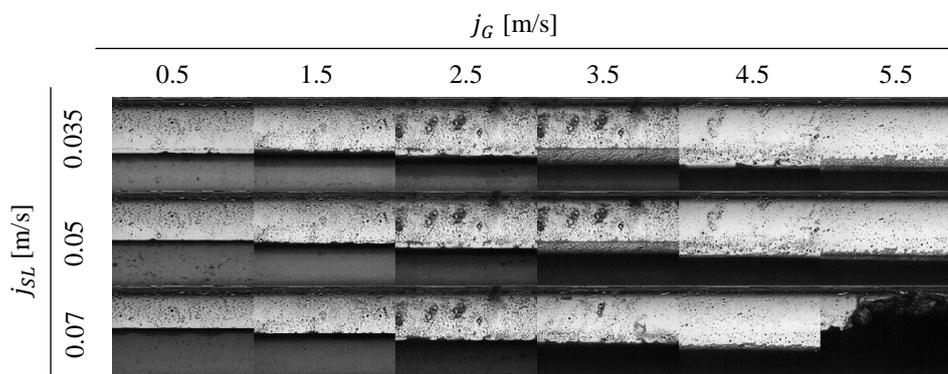


Figure 4. Flow images as a function of both gas and liquid superficial velocity for 5% v/v particle concentration

For 10% v/v of particles, the flow configuration changed for low gas superficial velocities. When j_G was equal to 0.5 m/s, due to the low phases superficial velocity, the flow turbulence was not enough to ensure particle dispersion, hence, as a result of buoyancy, particles floated and accumulated at the interface as a layer of solids, similarly to what was seen for 5% v/v. But in this case, due to the increased particle concentration, this solid bed at the interface was poorly transported and increase in size over time, at the test section inlet, to the point were almost all the pipe cross-section was blocked, as can be seen in Figure 5.



Figure 5. Thick particle layer at the interface at the test section inlet

When j_G was increased to 1.5 m/s, the layer of solids was still formed, but it builded over time until the point where the shear promoted by the gas was enough to destabilize the system leading to the formation of a structure similar to a slug, that is shown in Figure 6.



Figure 6. Plug transportation that occurred for 10% v/v and 20% v/v of particle concentration

This process occurred cyclically: building of the solid layer – flow destabilization resulting in a plug of solids – stratified flow recovery – building of the solid layer. Since the cycle had a period of minutes, it was not characterized as slug flow, instead as a plug transportation due to the gas blowing the layer of accumulated solids at the interface. Interestingly a similar phenomenon was reported by Wang et al. (2019) when studying coal transportation in stratified flow pattern. For them, the transition between stratified and slug flow occurred by two mechanisms, the first was the well-known wave growth, while the second was due to the formation of an unstably high coal particle bed. The second mechanism was also described as cyclic, since the increased solid-carrying capacity of slug flow was able to quickly decrease the critical height of the coal bed, which after the passage of the slug started to build again, similarly to what was saw in the present work.

For gas superficial velocities higher than 2.5 m/s regular stratified flow was recovered, with behavior similar to that observed with 5% v/v, i.e. particles got more homogeneously dispersed within the liquid layer with the phases' superficial velocity.

When particle concentration was increased to 20% v/v of particles, the plug transportation mode was the main pattern observed for the test conditions investigated in the present work. Regular stratified flow was only observed for gas velocities equal or higher than 4.5 m/s.

Hence, as can be seen, the increase in particle concentration can result in profound changes in the flow pattern.

5. INFLUENCE OF THE PARTICLE CONCENTRATION ON THE PRESSURE DROP

The pressure drop (dp/dx) as a function of the gas superficial velocity and the particle concentration is shown in Figure 7 for two different liquid/slurry superficial velocities ($j_{L/SL} = 0.035$ m/s and $j_{L/SL} = 0.06$ m/s).

As can be seen, the pressure drop is slightly higher for 5% v/v in comparison to the values found without particles. Still, no major changes in the tendency of the data with the phases' superficial velocity is seen. This can be explained by the fact that, although the phases' superficial velocity impacted in the solid distribution, the amount of particles did not generate enough particle-particle and particle-wall interaction to result in a noticeable change in the pressure drop behavior.

On the other hand, the effect of phases' superficial velocity on the pressure loss is much more significant for 10% v/v of particles. This is intrinsically related to the flow patterns presented early. In Figure 8 (a), the pressure drop time series for $j_G = 0.5$ m/s and all the slurry superficial velocities that resulted in the formation of the slow moving layer of solids at the interface, is shown.

As can be seen, the pressure loss increases with time until a fairly constant value is achieved. As aforementioned, in these operational conditions, solids were so poorly transported that they started to accumulate at the interface as layer of solids. As the layer increases in size, the amount of particle-particle and particle-wall interaction increase as well, thus resulting in the increase of the pressure loss over time. Eventually a steady layer size is achieved leading to a steady pressure drop.

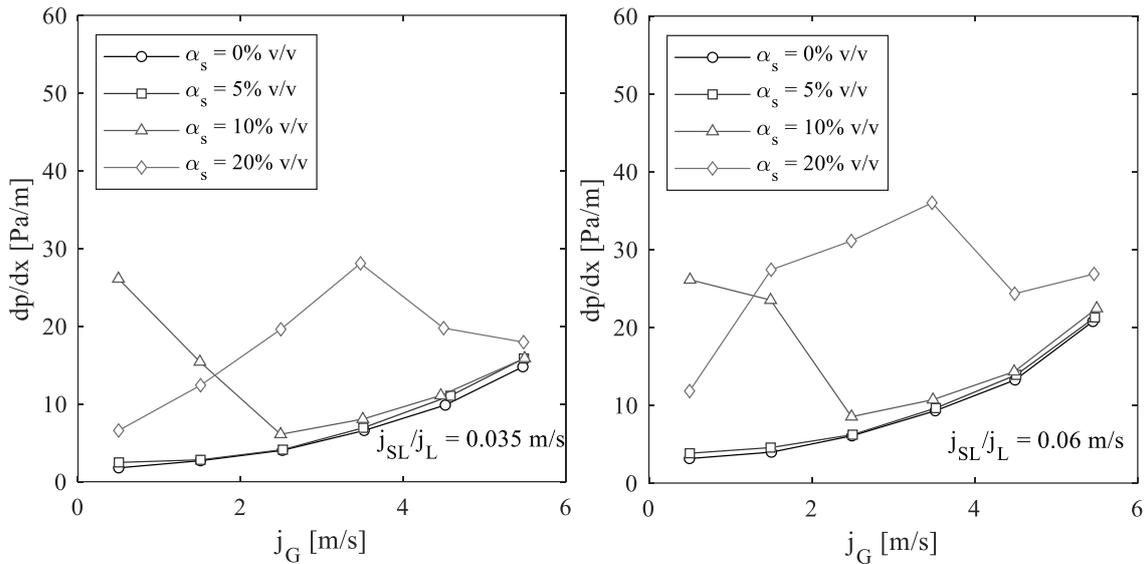


Figure 7. Pressure drop as a function of the gas superficial velocity and the particle concentration for $j_{L/SL} = 0.035$ m/s and $j_{L/SL} = 0.06$ m/s.

When the gas velocity is increased to 1.5 m/s, particles transportation is increased due to the formation of the liquid-solid plugs. Similarly to a slug flow pressure signal, during the stratified flow region the pressure drop is smaller while when the plugs are passing, a peak on the pressure drop is noticed, as depicted in Figure 8 (b) for $j_G = 1.5$ m/s and $j_{SL} = 0.04$ m/s. Although it is noteworthy that a decrease of the dp/dx in comparison to the cases in which $j_G = 0.5$ m/s can be noticed, which is related to the increase in particle transportability. When the superficial velocity is increased to 2.5 m/s stratified flow is guaranteed and the expected stratified flow pressure drop behavior is recovered, although with slightly higher values than with the lower concentrations.

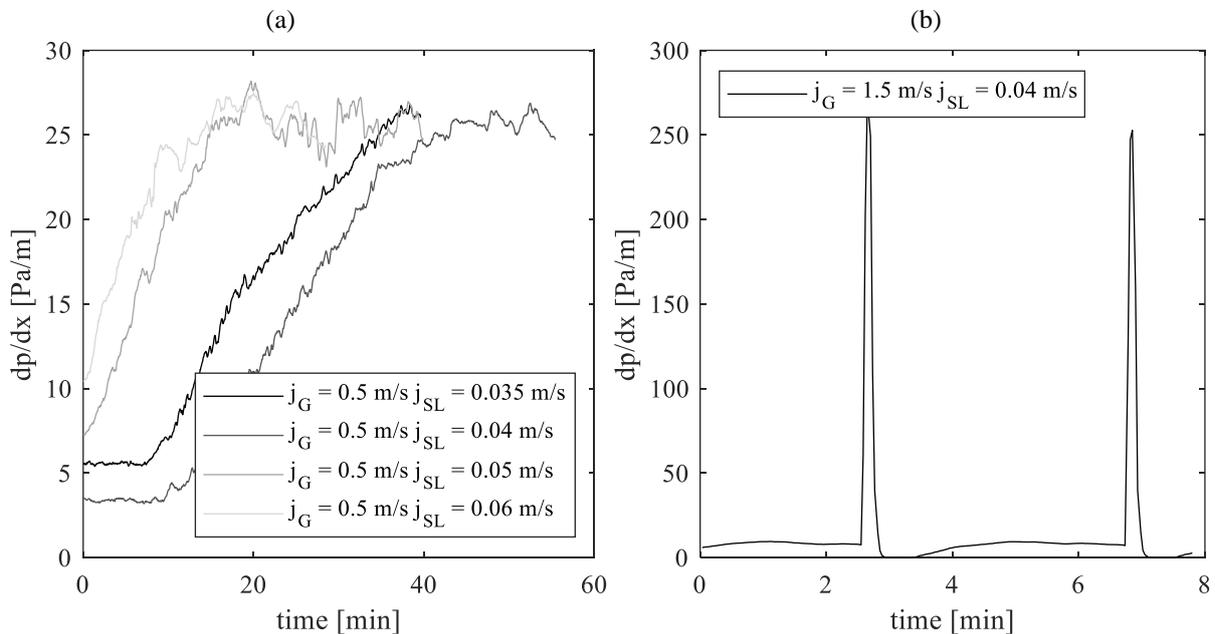


Figure 8. Pressure drop time series for the cases: (a) $j_G = 0.5$ m/s and slurry superficial velocities that generated the slow moving layer of solids at the interface, and (b) $j_G = 1.5$ m/s and $j_L = 0.04$ m/s.

For 20% v/v the pressure drop increase with the gas superficial velocity when in the plug transportation pattern, but faces a decrease when the regular stratified flow is recovered. Again, dp/dx is slightly increased in comparison to the lower concentrations studied.

6. INFLUENCE OF THE PARTICLE CONCENTRATION ON THE LIQUID LEVEL

The effect of the particle concentration on the mean liquid level, made dimensionless by dividing it by the pipe diameter (h_L/d) is shown in Figure 9, where the results for the cases with particles are plotted against those without particles. It is noteworthy that the liquid height results comprise only the cases in which stratified flow pattern occurred.

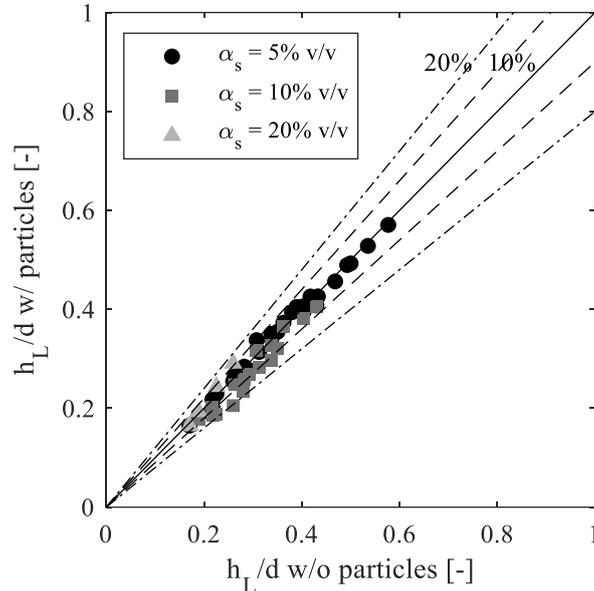


Figure 9. Liquid height for the cases with particles plotted against the case without particles.

As can be seen, the majority of the results lie in a range of 20% of variation, hence the presence of particles has a minor effect on the mean liquid height for the conditions investigated in the present work.

7. CONCLUSION

In the present work the case in which hydrates are allowed to form and are transported within the liquid phase in a stratified gas-liquid-solid configuration was experimentally emulated using air, water and polyethylene particles as the working phases.

The results showed that the particles have a big effect on the flow pattern. In conditions in which stratified flow is considered stable according to the Viscous Kelvin Helmholtz criteria, mainly for the higher concentration cases, operating with small gas velocity condition, two different patterns were seen: stratified flow pattern with a slow moving bed flowing at the interface and plug transportation.

These different patterns profoundly affected the behavior of the pressure drop. These new observed patterns were much more energy consuming than the regular stratified flow. A common trend was found when the stratified flow regime occurred, the pressure drop increased with the increase of the particle concentration.

Finally, by plotting the results for the average liquid level of the stratified flow, it was seen that the variation on the particle concentration had minor effects on it, with the differences between the results with and without particles lying in a range of 20%.

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9. RESPONSIBILITY NOTICE

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