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Sand transport in multiphase flow mixtures in a horizontal pipeline: An experimental investigation

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ABSTRACT

An inherent problem with both oil and natural gas production is the deposition of sand particles in pipeline, which could lead to problems such as excessive pressure drops, equipment failure, pipeline erosion, and production decline. The characterization of sand particles transport and sedimentation in different flow systems such as sand–multiphase mixtures is vital to predict the sand transport velocity and entrainment processes in oil and gas transportation pipelines. However, it seems that no model exists able to accurately characterize the sand transport and deposition in multiphase pipeline. In fact, in the last decade several researchers tried to extend the modeling of liquid-solid flow to gas-liquid-solid flow, but no significant results have been obtained, especially in slug flow condition due to the complexity of the phenomenon. In order to develop and validate a mathematical model properly formulated for the calculation of the sand critical deposition velocity in gas-liquid flow, more and more experimental data are necessary. This paper presents a preliminary experimental study of three phase flows (air-water-sand) inside a horizontal pipe and the application of the sand-liquid models present in literature. Significant observations were made during the experimental study from which several conclusions were drawn. Different sand flow regimes were established by physical observation and data analysis: fully dispersed solid flow, moving dunes and stationary bed. The critical deposition velocities were determined at different sand concentrations. It was concluded that sand transport characteristics and the critical deposition velocity are strongly dependent on the gas-liquid flow regime and on sand concentration.

1. Introduction

Flow assurance involves ensuring fluid flow in well, flowline and trunkline and consists of safe and efficient delivery of oil and gas products from the well to the collection facilities, through the predictions of possible problems occurring during the transportation (such as liquid loading, wax deposition, sand deposition, etc.) [1] or across particular equipment (such as multiphase valves) [2] and the definition of possible remediation. In particular, the sand transport topic has received scant attention in the literature in the last years [3,4]. In fact, sand frequently affects the production from unconsolidated oil and gas reservoir from reservoirs with low formation strength. Other three causes of the sand in production oil and gas systems can be identified in literature: high reservoir fluid viscosity, pore pressure reduction and increase in water cut. Many reservoirs from major oil and gas producing regions (such as Gulf of Mexico, North Sea, Middle East) are prone to sand production due to their unconsolidated formations and high sand production potential during the life of the well. Phenomena such as sand

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deposition can lead to partial or complete blockage of flowlines, enhanced pipe bottom corrosion, and trapping of pigs. These failures can cause unexpected downtime and risk to equipment as well as personnel. If sand production is expected, some techniques can be used to avoid the intrusion of sand into the pipeline including the down-hole sand exclusion systems such as gravel packs and screens; however, these techniques may cause a significant loss in productivity. Moreover, the removal of sand using pigging may be relatively simple, but this cleaning operation is useful only for small amount of deposits. For these reasons, the development of sand production management strategies has become a conventional method for the exploitation of the Oil and Gas worldwide resources. A production system affected by sand and correctly designed operates above the critical sand deposition velocity, and solid particles are dispersed in fluid phases. Ineffective sand transport in production and transfer systems can result in severe problems such as productivity impairment, sand deposition, bed formation, sand erosion, corrosion, and equipment failure. Because the implications and costs of operating below the critical deposition velocity are so high, adequate knowledge of sand transport characteristics in oil-gas multiphase pipelines is highly required. Though a vast number of theoretical and experimental studies on liquid-sand flow can be found in literature, very few studies relating the gas-liquid-sand flow are available and uncertainties exist for the modeling of this flow.

1.1. Literature review

1.1.1. Sand-water flow

In the past 60 years, several authors investigated liquid-sand flow and developed a correlation to determine deposit velocity in hydraulic slurry transport. Durand [5] conducted a series of test with sand, coal, and gravel. He defined critical velocity as velocity at which particles can be transported without forming a stationary bed with minimum head loss, and in his correlation considered the effect of concentration, pipe diameter, particle size, solid density, and liquid density. Condolios and Chapus [6] developed critical velocity correlation for v/v concentration less than 0.02 while Thomas [7] mathematically described the sand motion for particles sizes below and above thickness of the laminar sub layer. Charles [8] introduced a new correlation for critical velocity based on the idea that minimum pressure gradient corresponds to the velocity at which particles begin to deposit. Starting from the results of Durand [4] and Condolios and Chapus [6], Charles [8] developed an equation to correlate sand, fluid density, pipe, and particle diameter with the velocity at which solid particles deposit. Wicks [9] analysed experimentally the effect of water and kerosene with a low sand concentration. He proposed a mathematical model based on his definition of the critical velocity: the condition when the drag, lift and buoyant forces, which tend to cause rotation of the particle, exceed the gravity force, which tend to hold the particles in place. Oroskar and Turian [10] developed a correlation for the critical velocity considered as the minimum velocity demarcating flows in which the solids form a bed at the bottom of the pipe from fully suspended flows based on the energy balance required to suspend particles from dissipation of a fraction of the turbulent eddies. This correlation is widely used to predict critical velocity in liquid-solid horizontal pipes. Later, Turian [11] extended his study and developed a new correlation based on a wide range of sand particles. He concluded that critical velocity is weakly influenced by the particle diameter. Doron et al. [12] introduced a new fluid layer model. They argue that low velocity flow can be divided into three different layers: stationary bed, moving bed on the layer, and a heterogeneous suspended mixture on the top layer. They defined the critical velocity as the stream velocity when the stationary bed layer is zero. Kokpinar and Gogus [13] developed an empirical correlation to predict critical velocity, defined as velocity below which deposits will occur but above which no deposits in the pipeline will be encountered. Al-Mutahar [14], following the approach of Davies [15] and Oroskar and Turian [10], defined the critical velocity as minimum stream velocity needed for keeping sand particles in suspension in pipe flow to prevent sand deposition.

1.1.2. Sand-gas-water flow

Scott and Rao [16] carried out the first experimental study about the transport of solids by 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. Saltation velocity was defined as the velocity required to keep the solid particles barely skimming along the bottom of the horizontal pipe. Their experimental results were in a good agreement with Durand model [5]. Oudeman [17] studied the influence of gas fraction for high sand concentration and developed a correlation based on experimental data. Oudeman [17] found that the transition from moving bed to suspension takes place at higher superficial velocities than the transition velocity from stratified wavy flow to slug flow and concluded that gas-liquid flow regime has no direct influence on the sand transport mode. Moreover, the effect of liquid viscosity and particle size on the sand transport is limited while the gas fraction influenced greatly the sand transport. Gillies et al. [18] presented a correlation very similar to the Oudeman model [17] to describe solid transport in multiphase systems. Three-phase air-water-sand and air-oil-sand flows were used for experimental tests in a horizontal line. Authors found that the gas injection had a little influence on the sand transport when the flow was laminar while for turbulent flow the solid transport increases. Salama [19] proposed a model for estimating the critical deposition velocity for three-phase flows. Starting from the modified Wicks [9] and Oroskar and Turian [10] models, Salama [19] developed a correlation applicable for low sand concentration. Stevenson et al. [20] investigated 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. Danielson [33] performed several experimental tests with different gas and liquid fluids. He found that the gas fraction has no direct influence on the critical slip velocity between the sand and the carrier liquid, while the sand bed formation is strongly dependent on the inclination angle. Danielson [33] also used OLGA code to determine the sand hold-up along the line and he obtained good fit data for both liquid-solid and gas-liquid-solid experiments. Bello [34] presented a mathematical model and computational algorithm to estimate the optimal transport velocity, particle velocity, particle holdup, and critical velocity in three-phase flow. The model shows a good agreement with the experimental data. Goharzadeh et al. [35] analysed experimentally the air-water-sand slug flow inside a horizontal pipe for high sand concentrations. Results shown that the gas ratio does not affect sand transport velocity; however, slug flow significantly influences sand particle mobility. Al-lababidi et al. [21] studied the effect of the pipe inclination on the critical sand velocity. Although minimum sand transport velocity is little affected by inclination in water-sand flow, for the three-phase flow the pipe inclination modifies the gas-liquid flow regime and consequently the sand-transport mechanism. The model, based on Oroskar and Turian [10] correlation for two-phase flow and the Salama [19] correlation for three-phase flow, shown a good agreement with literature data, especially for a pipe diameter of 0.1 m. Dabirian et al. [22] investigated sand flow regimes in air-water stratified flow in horizontal pipes for various sand concentrations. Bello and Oyeneyin [23] carried out an experimental investigation of the minimum transport velocity in both two-phase water-sand and three-phase air-water-sand flow. They found that the minimum transport velocity is greatly influenced by the flow patterns and that the slug flow provides best solid carrying capacity in pipe. Moreover, minimum transport velocity is strongly dependent from pipe inclination. Considering the complexity of the multiphase sand transport and the uncertainty in the characterization of the liquid-sand transport in three-phase mixtures which all the above scientific works show, there is need to acquire useful experimental data in order to develop a general model to characterize this kind of flow. In particular, the effect of the sand concentration on two and three-phase flow is not completely clear, and the influence of the gas phase is still not well understood. In the present study, the minimum transport condition velocities in water-sand and air-water-sand flow at different sand concentration and for various sand particle size are investigated. Experimental data to test and validate theoretical models are collected.

1.2. Sand-flow regimes

Mechanisms of sand transport in a pipeline are function of flow velocity, fluid properties, pipe inclination, pipe geometry, particle size, and particle concentration. The characterization of different sand flow patterns is very difficult, especially in solid-gas-liquid multiphase flow and usually it is performed by direct visual observation and video recording. Many researchers tried to identify the several particle interactions and the various regimes. Durand [5] and then Condolios and Chapus [6] defined the sand transport in pipeline by two regimes: with and without a deposit. Shamlou [24] classified the sand flow patterns in horizontal pipelines as homogeneous flow, heterogeneous flow, heterogeneous and sliding flow, and saltation and stationary bed. Ercolani et al. [25] introduced a new classification of sand flow patterns recognising pseudo-homogeneous flow, heterogeneous flow, moving/stationary bed, moving dunes and stationary bed. Doron et al. [26] give a general classification of the flow patterns based on the solid distribution in the transportation line. According to Doron et al. classification [26], in the present work the following regimes have been identified: fully suspended flow with two sub-patterns, pseudo-homogeneous and heterogeneous flow, flow with moving bed, and flow with a stationary bed including saltation. In fully suspended flow the sand is transported in suspension or dispersed in the liquid phase. This type of suspension flow is generally observed at high suspension flow rates and it can be divided into pseudo-homogeneous suspension and heterogeneous suspension. For very high mixture flow rates, solid particles are distributed nearly uniformly across the pipe cross-section (pseudo-homogeneous) while decreasing the flow rate, most solid particles are transported at the lower part of the pipe cross-section forming a particle concentration gradient.

At lower mixture flow rates, solid particles accumulate at the pipe bottom and form a dense packed bed layer, which moves along the pipe bottom; regime is named moving bed. The concentration of this layer corresponds to maximum packing, or nearly so. A heterogeneous mixture characterizes the upper part of the pipe cross-section. Instead, dunes and stationary bed manifest for very low mixture flow rate when solid particles begin to deposit at the pipe bottom. Usually, when the solid concentration is very low, the moving bed develops in isolated slow-moving solid dunes. In the case of no dunes, with decreasing flow rate, a continuous stationary bed is created. On top of this deposit particles are transported as a separate moving layer. In many cases a phenomenon known as saltation, that is the formation of dune-like forms on the surface of the bed, can also be observed. The rest of the pipe is still occupied by a heterogeneous mixture, though its concentration profile is much steeper than in the other flow patterns.

1.3. Critical velocity

The critical velocity of sand transportation is defined as the velocity demarcating the transition between different sand flow patterns. Several authors introduced different definitions of transition velocity based on their classification of sand flow patterns; to mark the separation between the deposit and non-deposit flow regimes, Durand [4] proposed the limit deposit velocity. Wilson [28] and Toda et al. [29] defined the limit deposit velocity as the limit velocity for the stationary bed. Different authors like Stevenson [20] defined the critical deposition velocity as the transition velocity between the deposit and non-deposit flow regimes. Wood [30] and various authors based their definition of deposit velocity on the limit velocity for the stationary bed. Many authors ([25,10]) indicated the velocity below which there are deposited particles as critical velocity. Thomas [7] introduced the minimum transport condition (MTC) as "the mean stream velocity required to prevent

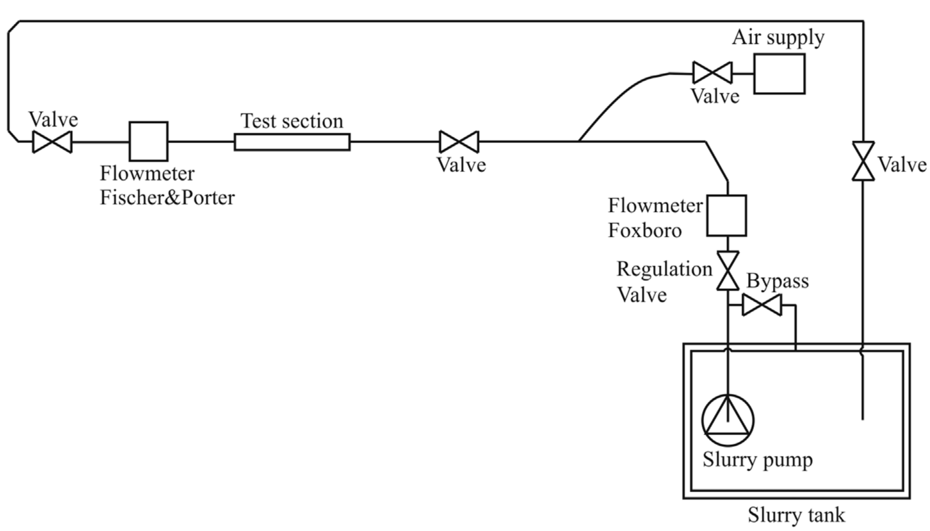

Fig. 1. Schematic of air-water-sand flow loop at DIISM.

Fig. 2. Picture of air-water-sand flow loop at DIISM. Test section.

the accumulation of a layer of sliding particles at the bottom of horizontal pipe". Spells [27] defined respectively the settling velocity and the minimum velocity as the velocity above which fully suspended flow is observed. Doron et al. [12] investigated the critical suspending velocity as the lowest velocity at which all particles are picked up and remain in suspension and the critical deposition velocity as the transition velocity between the stationary bed and moving bed. In the present work, the definition of Doron et al. [12] has been assumed in order to define the MTC. Based on this definition, the critical deposition velocity is studied for water-sand and air-water-sand flow in horizontal pipelines. Prevention of this limit deposit velocity is essential for the avoidance of the partial blockage of the pipelines. This reduces the efficiency of the pipelines and enhances pipe wear in field applications.

Fig. 3. Picture of air-water-sand flow loop at DIISM. Mixing tank and regulation valve.

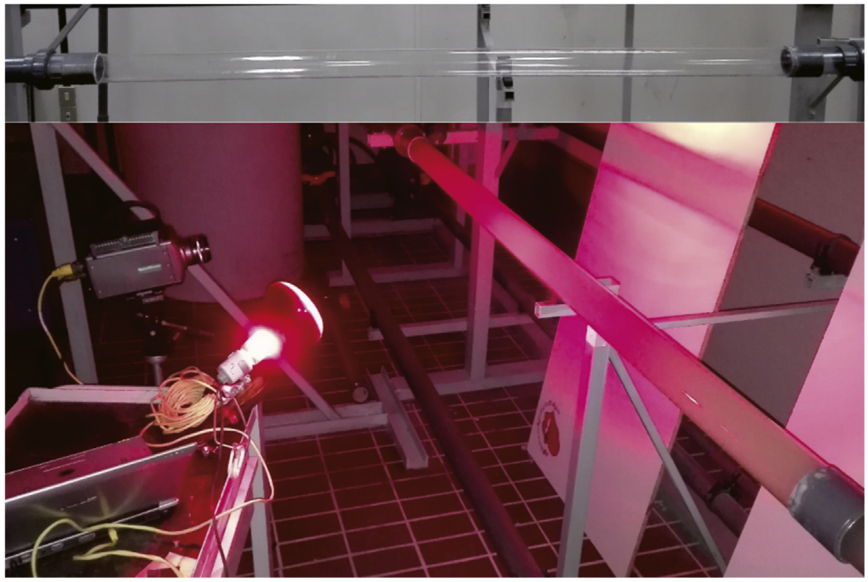

Fig. 4. Plexiglas test section and high-speed camera used to the flow patterns observations.

Table 1
Experimental test matrix

Variable	Range	Units
Pipe inner diameter	0.063	m
Sand density	1340, 1410	kg/m^3
Sand particle size	100-900, 100-1100	μm
Sand concentration, C_v	$6.5\ 10^{-5}$ - $5.6\ 10^{-4}$	v/v
Superficial liquid velocity, V_{sl} - (water-sand test)	0–1	m/s
Superficial liquid velocity, V_{sl} - (air-water-sand test)	0.01, 0.05, 0.1, 0.2, 0.5	m/s
Superficial gas velocity, V_{sg}	2–20	m/s

2. Materials and methods

2.1. Experimental setup

A multiphase air-water flow loop with 2.5-inch diameter PVC pipe has been designed and constructed at the Industrial Engineering and Mathematical Science Department (DIISM) of the Università Politecnica delle Marche. The scheme of the multiphase loop is shown in Fig. 1, while Fig. 2 and Fig. 3 report the pictures of the flow loop. In particular, Fig. 2 represents the view test section and Fig. 3 shows the part of the loop upstream the test section, i.e. the mixing tank and the regulation valve described in the following. This is a typical laboratory loop used for experiments related to multiphase mixture transport [31,32].

The total flow length of the loop is 25 m with a 2-m long test section for the flow visualization. Sand-water mixture is prepared through a mixing system build up in a tank with capacity of approximately 1 m^3 and pumped on the flow loop using a centrifugal pump with maximum flow rate of 18.5 m^3/h. The slurry flow rate is controlled by a manual valve located downstream the centrifugal pump and metered using an electromagnetic flow meter, Foxboro 8000-TB13 series (range: 0–20 m^3/h). Moreover, an electromagnetic flow meter Fischer&Porter MiniMagX (range: 0–20 m^3/h) is installed downstream of the test section. A recirculation line injects the slurry to the bottom of the tank, in a drilled pipe arranged along the inner perimeter of the reservoir; this layout is used to ensure a homogeneous slurry during the test. The air is provided by a centrifugal fan powered by an electric motor. It

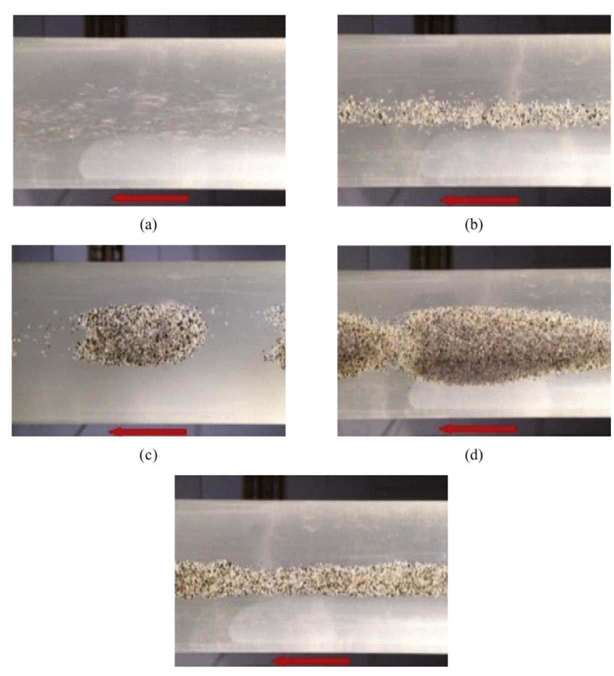

Fig. 5. Different type of observed sand flow regimes: (a) Suspension, (b) Moving bed, (c) and (d) Moving dunes, (e) Stationary bed (images of the bottom of the pipe) - Arrows indicate the flow direction.

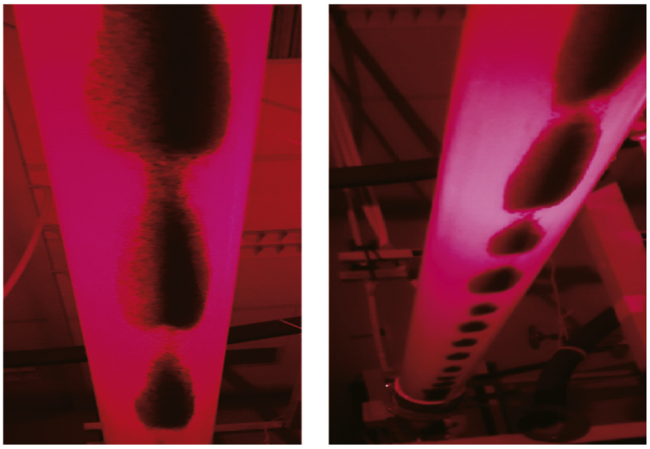

Fig. 6. Different type of observed sand flow regimes: transition from moving bed to moving dunes.

is injected upstream the test section and downstream the water flowmeter. To measure the air flow rate, a Foxboro vortex flow meter, E83L-1HS40SIT model (range: 0–200 Nm^3/h) is used. A Schneider Electric inverter, ATV312HU55N4 model, is used to control the air flow rate.

The flow pattern observations have been made through clear Plexiglas sections during the experimental runs. A high-speed digital video camera having 256×256 pixel resolution has been used to record video and images in order to visualise the flow patterns (as shown in Fig. 4).

2.2. Water-sand and air-water-sand flow test procedure

In order to evaluate the MTC, water-sand tests have been carried out with different sand concentrations, particle sand size, and flow velocity as reported in Table 1.

Two different particle sizes of dry silica sand (SiO_2 75.62%) have been used: fine sand and medium sand, with particle diameter ranging, respectively, from 100 to 900 μm and from 100 to 1100 μm and average densities of 1340 and 1410 kg/m^3. Prior to the sand experiments, only the by-pass line was open to ensure a homogeneous mixture and then the regulation valve has been completely opened to pump the slurry flow into the loop. At this condition, the electromagnetic flow meter measured a velocity of 1 m/s. Sand particles were completely suspended in the liquid phase. After 15 min, when the flow reached a stationary condition, tests about sand behaviour have been started. In order to observe the sand behaviour, the superficial liquid velocity, V_{sl}, was reduced step by step by using the manual regulation valve. At the end of the experiments with the decreasing liquid velocity, the pipe presented a stationary sand bed on the bottom. Then, the regulation valve has been gradually re-opened to increase the slurry velocity from 0 to 1 m/s. The two different variations of the velocity (increasing and decreasing) have been defined by the authors as "velocity history" and its influence on the sand deposition behaviour has been also investigated. Critical suspended velocities have been determined by visual method based on the transition between stationary bed and moving bed sand flow regime. Air-water-sand flow has been investigated in stratified (smooth and wavy) and slug flow regimes. The test procedure was similar to the water-sand one; the slurry was injected into the loop at desired superficial velocity and then superficial air velocity, V_{sg}, was regulated through the inverter. Superficial gas velocity was reduced step by step from 20 to 2 m/s; for each combination of superficial gas/liquid velocity, the sand flow regime was observed to find the transition between moving bed (or dunes) and stationary bed (or dunes).

3. Results

3.1. Water-sand flow

The results of the conducted tests with water-sand flow are presented in Fig. 5 - Fig. 9.

The wide range of experimental test conditions used in this work allowed to identify all the sand flow regimes described in the previous section. Fig. 5 and 6 show the different sand flow patterns determined by visual method. The critical deposition velocity was found at the transition from moving bed or moving dunes (5b, c and d) to stationary bed (5e). Table 2 and Table 3 summarize the effects

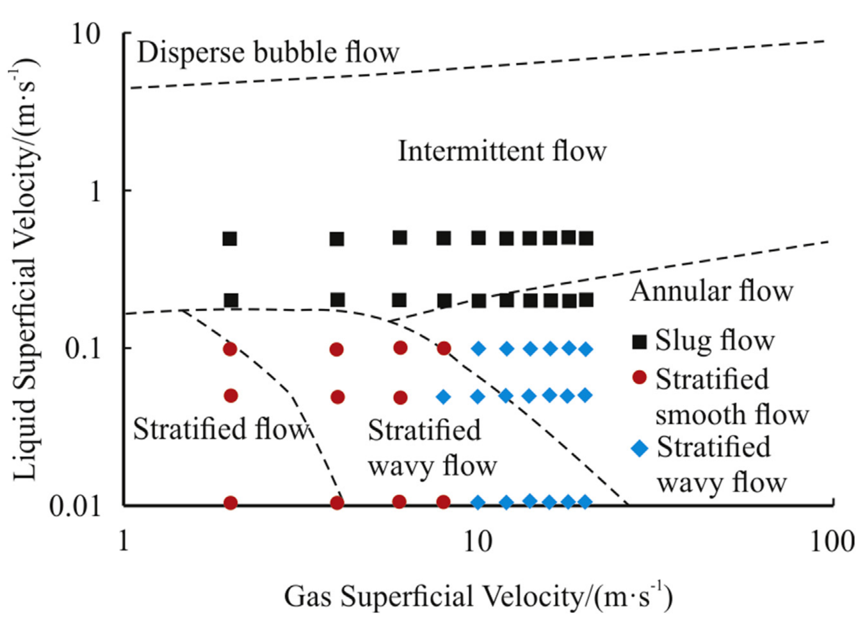

Fig. 7. Comparison between Taitel-Duckler [34] and observed air-water-sand horizontal flow regime map.

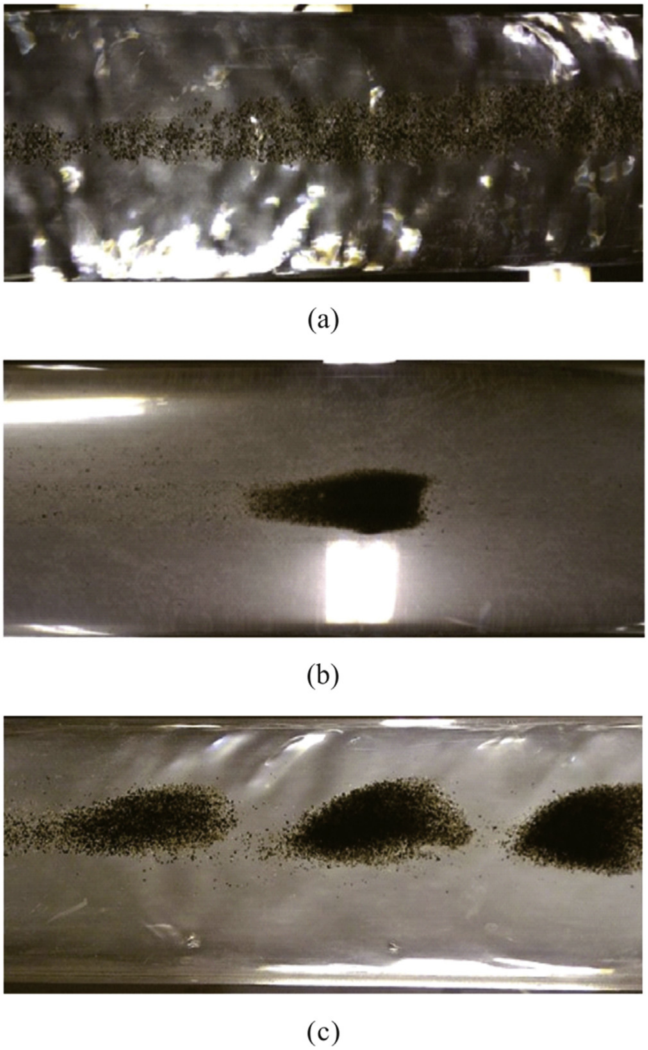

Fig. 8. Sand flow patterns observed at $V_{sl} = 0.05$ m/s and 6.5 10^{-5} v/v fine sand concentration: (a) $V_{sg} = 16$ m/s, (b) Vsg = 14 m/s, (c) $V_{sg} = 12$ m/s (images of the bottom of the pipe).

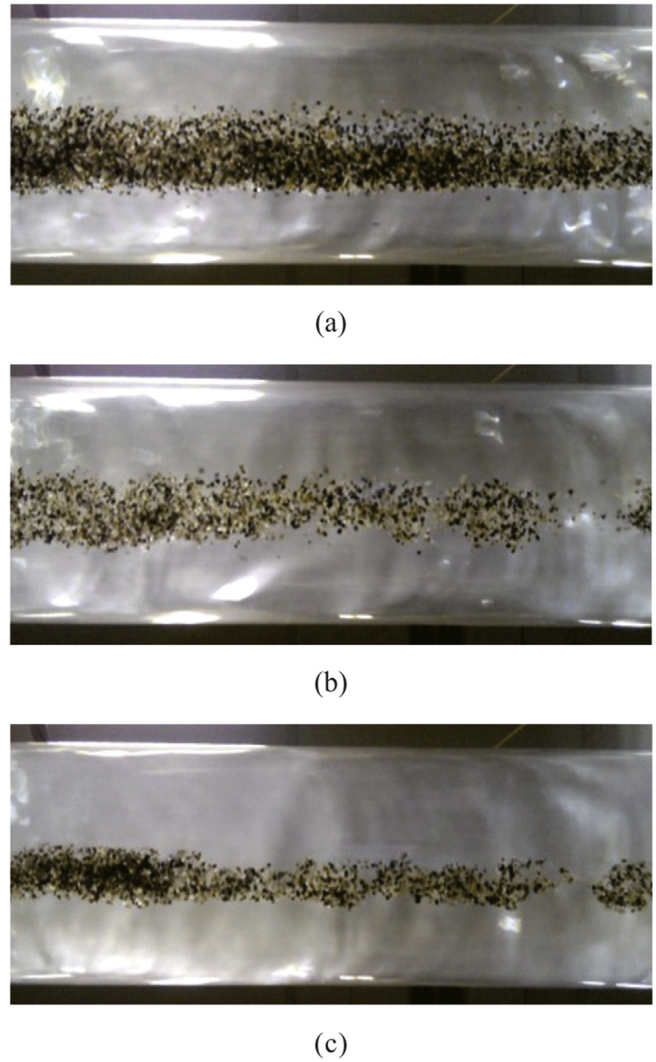

Fig. 9. Sand flow patterns observed at $V_{sl} = 0.05$ m/s and 6.5 10^{-5} v/v medium sand concentration: (a) $V_{sg} = 16$ m/s, (b) $V_{sg} = 14$ m/s, (c) $V_{sg} = 12$ m/s (images of the bottom of the pipe).

of the sand concentration, particles' diameter and velocity history and compare the MTC values obtained experimentally and calculated through the most credited models found in literature. The diameter of the sand particles highly influences the required velocity to reach the critical velocity (MTC). In tests with fine sand (Table 2), the MTC is lower than in tests conducted with medium sand. Using fine particles, the increase of the sand concentration caused an increase of the critical velocity for all the cases. The same trend is obtained by using medium sand with concentration between 2.2 10^{-4} and 5.61 10^{-4}. However, no significant change was observed analysing a slurry flow with sand concentration between 6.5 10^{-5} and 2.2 10^{-4}. The variation of the velocity history gives interesting results: in all the cases where the slurry velocity decreases, the critical deposition velocity is higher than the cases with an increasing velocity. In the future, this particular behaviour will be deeply investigated. In addition, it was found that some of them are unable to predict with accuracy the critical deposition velocity. Durand [5] and Condolios and Chapus models [6] overestimate the sand deposition velocity while relationships developed by Charles [8], Danielson [33] and Kokpinar and Gogus [13] underestimate it. The model introduced by Oroskar and Turian [10] provides results closer to experimental values for concentration between 2.16 10^{-4} to 6.44 10^{-4} and increased velocity but it underestimates the MTC for concentrations below 2.16 10^{-4}.

3.2. Air-water-sand flow

In order to understand the sand transport behaviour under different air-water flow conditions, the flow regime characteristic of the test flow loop have been identified prior to the sand experiments. The flow conditions for all experimental runs are plotted on a Taitel and Dukler [36] flow pattern map (Fig. 7).

As can be seen, stratified smooth flow, stratified wavy flow and slug flow have been observed. It is clear that the observed and predicted flow regimes are not exactly matched when the flow regimes are within the stratified wavy flow and annular flow, as found also by Al-lababidi et al. [21]. At each experimental point, it has been associated one of the three sand regime flows: stationary bed (SB), moving bed (MB), and suspension (S), in order to characterize the critical deposition velocity. Table 4 shows all the observed regime flows; the transition from stationary bed to moving bed that characterizes the critical deposition velocity only occurs for the stratified regime flow. When the observed regime

Table 2
Experimental and numerical critical velocities (fine sand)

		Critical velocity [m/s]	
		Cv [v/v]	
		2.85E-04	6.44E-04
Fine type sand	Durand (1953) [5]	0.52	0.52
	Condolios e Chapus (1963) [6]	0.67	0.76
	Charles (1970) [8]	0.07	0.09
	Oroskar e Turian (1980) [10]	0.26	0.29
	Kokpinar e Gogus (2001) [13]	0.20	0.25
	Danielson (2007) [33]	0.18	0.18
	Critical deposition velocity - Increased Velocity	0.3	0.35
	Critical deposition velocity - Decreased Velocity	0.35	0.45
	Critical suspending velocity - Increased Velocity	0.65	0.7
	Critical suspending velocity - Decreased Velocity	0.6	0.7

Table 3
Experimental and numerical critical velocities (medium sand)

		Critical velocity [m/s]			
		Cv [v/v]			
		6.55E-05	2.16E-04	2.25E-04	5.61E-04
Medium type sand	Durand (1953) [5]	0.55	0.55	0.55	0.55
	Condolios e Chapus (1963) [6]	0.65	0.64	0.65	0.74
	Charles (1970) [8]	0.05	0.07	0.07	0.10
	Oroskar e Turian (1980) [10]	0.23	0.28	0.28	0.32
	Kokpinar e Gogus (2001) [13]	0.14	0.20	0.20	0.26
	Danielson (2007) [33]	0.21	0.21	0.21	0.21
	Critical deposition velocity - Increased Velocity	0.35	0.35	0.35	0.4
	Critical deposition velocity - Decreased Velocity	0.4	0.4	0.4	0.5
	Critical suspending velocity - Increased Velocity	0.65	0.75	0.75	0.8
	Critical suspending velocity - Decreased Velocity	0.75	0.65	0.65	0.65

flow is slugged at the minimum superficial air velocity, the observed sand regime is moving bed, therefore critical deposition velocity cannot be determined.

Sand flow characteristics under stratified flow regime are now described. With a sand volume fraction of 6.5 10−5, V_{sl} equal to 0.05 m/s and V_{sg} of 16 m/s, the fine sand flow is moving bed (Fig. 8a).

A thin layer of solid particles settles on the bottom of the pipe and a considerable number of particles moves around this bed following the air-water flow. At the same liquid velocity and with a lowering superficial air velocity, the smooth bed starts to split up and it forms a structure similar to moving sand dunes (Fig. 8b). By continuing to reduce the superficial air velocity, sand dunes reduce their moving velocity and their size increases (Fig. 8c). The critical deposition velocity is achieved when the superficial air velocity reaches 10 m/s; at this condition moving sand dunes turn into a uniform stationary bed. By increasing the sand volume fraction, the critical deposition velocity is reached at a higher superficial air velocity, but the characteristics of sand flow described above remain the same. Using medium sand at high superficial air velocity, it can be seen a moving bed similar to the one obtained with fine sand (Fig. 9a).

However, by reducing the air superficial velocity no dunes are formed, but a continuous moving layer of sand particles can be observed at the bottom of the pipe until the flow reaches the critical deposition velocity (Fig. 9b–c). It is interesting to study the critical deposition velocity versus the superficial gas velocity for different sand particle diameters and sand concentrations. For the same particle size and gas velocity, the increase of the sand concentration causes an increase of the critical deposition velocity. The same trend can be observed by considering various particle dimensions at constant gas velocity and sand concentration. Moreover, as the gas superficial velocity increases, the critical deposition velocity decreases. For what concerns the slug flow, the determination of critical deposition velocity is really complex because it is difficult to identify the right sand flow regime. The mechanisms of sand transportations are very different from the ones described for stratified flow and they are still not very clear. Stevenson et al. [20] and Al-lababidi et al. [21] tried to explain these mechanisms of transportation dividing the flow in two zones: the slug body, a very energetic zone where the sand particles start to move and gain a great amount of energy that derives from the turbulence of the slug front, and the film zone, in which sand particles velocity starts to decrease. Sand particles are transported in an intermittent way; a sand flow regime similar to the suspension can be seen during the passing of the slug front and a sand flow regime similar to moving bed or stationary bed can be seen between two consecutive slug fronts. According to these studies, the present work highlights that an increase of the superficial gas velocity causes an extension of the film zone and, as a consequence, there is an increase of the sand deposition thickness in this area. Critical deposition velocity for slug flow cannot be determined with the analysed operating conditions. This aspect will be investigated in the future.

4. Conclusions

The effects of the sand concentration and sand particle size on the critical deposition velocity have been experimentally investigated in both water-sand and air-water-sand flow. Stratified (smooth and wavy) and slug flow regime have been studied in a horizontal pipe with an internal diameter of 0.063 m. For water-sand flow with sand concentration above 2.25 10^{-4}, the critical velocity is greatly influenced by the sand properties (size and concentration). Below this concentration value, only the particle

Table 4
Observed sand flow regime for each test condition

V_{sl}	V_{sg}	Flow regime	Fine sand			Medium sand		
			$6.5\ 10^{-5}$	$2.2\ 10^{-4}$	$5.6\ 10^{-4}$	$6.5\ 10^{-5}$	$2.2\ 10^{-4}$	$5.6\ 10^{-5}$
m/s	m/s	–	v/v	v/v	v/v	v/v	v/v	v/v
0.01	2	Stratified smooth	SB	SB	SB	SB	SB	SB
0.01	4	Stratified smooth	SB	SB	SB	SB	SB	SB
0.01	6	Stratified smooth	SB	SB	SB	SB	SB	SB
0.01	8	Stratified smooth	SB	SB	SB	SB	SB	SB
0.01	10	Stratified wavy	SB	SB	SB	SB	SB	SB
0.01	12	Stratified wavy	SB	SB	SB	SB	SB	SB
0.01	14	Stratified wavy	SB	SB	SB	SB	SB	SB
0.01	16	Stratified wavy	SB/MB	SB	SB	SB	SB	SB
0.01	18	Stratified wavy	MB	SB/MB	SB	SB	SB	SB
0.01	20	Stratified wavy	MB	MB	MB	MB	MB	SB
0.05	2	Stratified smooth	SB	SB	SB	SB	SB	SB
0.05	4	Stratified smooth	SB	SB	SB	SB	SB	SB
0.05	6	Stratified smooth	SB	SB	SB	SB	SB	SB
0.05	8	Stratified wavy	SB	SB	SB	SB	SB	SB
0.05	10	Stratified wavy	SB	SB	SB	SB	SB	SB
0.05	12	Stratified wavy	MB	SB	SB	SB	SB	SB
0.05	14	Stratified wavy	MB	MB	MB	MB	SB	SB
0.05	16	Stratified wavy	MB	MB	MB	MB	MB	MB
0.05	18	Stratified wavy	MB	MB	MB	MB	MB	MB
0.05	20	Stratified wavy	MB	MB	MB	MB	MB	MB
0.10	2	Stratified smooth	SB	SB	SB	SB	SB	SB
0.10	4	Stratified smooth	SB	SB	SB	SB	SB	SB
0.10	6	Stratified smooth	SB	SB	SB	SB	SB	SB
0.10	8	Stratified smooth	SB	SB	SB	SB	SB	SB
0.10	10	Stratified wavy	MB	SB/MB	SB/MB	SB/MB	SB/MB	SB
0.10	12	Stratified wavy	MB	MB	MB	MB	MB	MB
0.10	14	Stratified wavy	MB	MB	MB	MB	MB	MB
0.10	16	Stratified wavy	MB/S	MB	MB	MB	MB	MB
0.10	18	Stratified wavy	S	MB/S	MB	MB	MB	MB
0.10	20	Stratified wavy	S	S	S	MB	MB	MB
0.20	2	Slug	MB	MB	MB	MB	MB	MB
0.20	4	Slug	MB	MB	MB	MB	MB	MB
0.20	6	Slug	MB	MB	MB	MB	MB	MB
0.20	8	Slug	MB	MB	MB	MB	MB	MB
0.20	10	Slug	MB	MB	MB	MB	MB	MB
0.20	12	Slug	MB	MB	MB	MB	MB	MB
0.20	14	Slug	MB	MB	MB	MB	MB	MB
0.20	16	Slug	MB/S	MB	MB	MB	MB	MB
0.20	18	Slug	MB/S	S	MB	MB	MB	MB
0.20	20	Slug	MB/S	S	S	MB/S	MB	MB
0.50	2	Slug	MB	MB	MB	MB	MB	MB
0.50	4	Slug	MB	MB	MB	MB	MB	MB
0.50	6	Slug	MB	MB	MB	MB	MB	MB
0.50	8	Slug	MB	MB	MB	MB	MB	MB
0.50	10	Slug	MB	MB	MB	MB	MB	MB
0.50	12	Slug	MB	MB	MB	MB	MB	MB
0.50	14	Slug	MB/S	MB	MB	MB	MB	MB
0.50	16	Slug	S	MB	MB	MB	MB	MB
0.50	18	Slug	S	S	S	S	MB	MB
0.50	20	Slug	S	S	S	S	S	S

size shows significant effects on the critical deposition velocity. Also, the velocity history has a considerable influence on the sand deposition velocity. A variation of the sand concentration and particle size in air-water-sand flow causes a change in sand deposition characteristics. The introduction of the gas phase widely reduces the critical value of deposition velocity and it was experimentally found that the sand transportation is more efficient when the slug flow is observed.

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