Accepted version. Final published version available online:
http://www.doi.org/10.1061/%28ASCE%29PS.1949-1204.0000427

An experimental study on sand transport characteristics in horizontal and inclined two-phase solid-liquid pipe flow

A. Archibong-Eso[1], A. M. Aliyu*[2], W. Yan[3]., N. E. Okeke[4], Y. D. Baba[5], O. Fajemidupe[6], H. Yeung[7]

[1]Department of Mechanical Engineering, Cross River University of Technology, Calabar, Nigeria
[2]Faculty of Engineering, University of Nottingham, NG7 2RD, United Kingdom
[3]Genesis Oil and Gas Consultants, London, One St Paul's Churchyard, EC4M 8AP, United Kingdom
[4]Department of Chemical Engineering, Edo University, PMB 04, Iyamho, Edo State, Nigeria.
[5]Department of Chemical/Petroleum Engineering, Afe Babalola University, PMB 5454, Ado-Ekiti, Nigeria
[6]Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Norman 100 E Boyd St. Norman, OK-73019, USA
[7]Oil and Gas Engineering Centre, Cranfield University, MK43 0AL, Cranfield, UK

ABSTRACT

An experimental investigation on the hydraulic transport of sand particles in pipelines is presented in both horizontal and 30° upward inclined orientations. The pipe, with an internal diameter of 0.0254 m, had sand transported in various water superficial velocities at low and high sand concentrations (0.1–10% v/v). Sand particles were polydisperse (144–250 µm) with a d_{95} of 210 µm. The minimum transport condition (MTC), was determined by means of video recordings and pressure gradient (PG) measurements. MTC and PG were observed to increase with increase in sand concentration and mixture velocity. At high sand concentrations, there was a decline in PG with decrease in flow velocity until a minimum is reached around the MTC. The MTC at which this occurs is different in the two pipe orientations. Based on a previously reported dimensionless relationship, a correlation was derived now including the effect of pipe inclination using extensive literature data in addition to the current. The effect of key flow, geometric and particle parameters were adequately captured in the improved closure relationship for sand minimum transport conditions in pipes.

Keywords: sand transport, minimum transport condition, pressure gradient, particle size, stratified flow.

Introduction

Background

Hydraulic transport of solids is encountered in an array of industries in the civil, chemical, food, mining, oil & gas and process industries (Danielson 2007, Najmi et al. 2015, Ibarra et al. 2014). This is especially prevalent in oil and gas production where the solid disperse phase is

*Corresponding author email:
alimaliyu@gmail.com (AM Aliyu)

undesirable as well as during river dredging where the slurries have to be transported away. In the oil & gas industry, sand is produced in fields with unconsolidated formations, in marginal fields, in ultra-deep water and even in unconventional resource fields. This usually happens when the field’s in situ strength exceeds the formation strength and also in fields with low formation strength (<1,000 psi) (Salama, 2000). Problems such as pipeline/well blockage, under-deposit corrosion/erosion of pipes, production/processing equipment damage and loss of production capacity are typical occurrences. Hence, when sand production is expected, field facility designers are faced with the choice of either designing for sand production control or sand production management systems. In the former, exclusion systems such as sandstone & expandable screens, gravel packs etc. are installed at a well’s inception or at the onset of sand production. Exclusion system failure, increased well pressure, reduced well productivity and in extreme cases, complete loss of well, has made this option sometimes untenable. Sand production management thus becomes imperative in those instances (Yan 2010, Archibong 2015).

To ensure non-deposition of produced sand at the bottom of pipelines, it is necessary to determine the minimum transport velocity required to keep the sand in suspension during flow, and operate above it. Determining this velocity is not straightforward as different definitions have been proposed by prominent investigators, a reason being that different mechanisms have been identified for solids transport in fluids. Another reason is that diverse names were used to define similar solids transport mechanism (Soepyan et al. 2014). As a result, it is important to adopt a definition as a basis, and here we use the widely accepted definition of the MTC given by Oroskar and Turian (1980). They defined the MTC as *“the minimum liquid velocity demarcating flows in which the sand form a bed at the bottom of the pipe from fully suspended flows”*. Sand transport in single phase liquid flow has been studied widely in literature with several empirical, semi-mechanistic and mechanistic models proposed. However, most of these studies were conducted for high sand concentration (>1% volume/volume) and horizontal pipe orientation. Additionally, recent advances in heavy oil production techniques has bolstered research in high viscosity oil based multiphase flows (Zhao et al. 2013, Archibong et al. 2015, Baba et. al. 2018, Archibong-Eso et al. 2018 & 2018b). Nonetheless, corresponding studies on solids transport in such scenarios are grossly lacking. This work will help set the basis for further studies in high viscosity multiphase flow applications especially because one of the most promising techniques used in heavy oil fields is the Cold Heavy Oil Production with Sand (CHOPS) (Archibong, 2015).

Theory

Shields (1936) was one of the first to apply dimensional similarity to sediment flows. As many uncertainties exist in turbulent flows and loose boundary materials, formulating critical shear stress analytically is difficult. However, Shields employed dimensional analysis to derive two important dimensionless variables namely the dimensionless shear stress (known as Shields number) and the particle Reynolds number given respectively as (Guo, 2002): $\tau/(s-1)\rho g d$ and $V^{*}d/\nu$ with τ being the sand or sediment bed shear stress, s the specific gravity of sand specific gravity, ρ the density of water, u^{*} is the shear or friction velocity given by $\sqrt{\tau/\rho}$, and ν is water's kinematic viscosity. Shields postulated that just when sediments begin to move, $\tau/(s-1)\rho g d = f(V^{*}d/\nu)$, determined experimentally. This relationship is graphed in what is called the Shields' diagram, and is essentially a force balance. However, it is rarely used in pipe flow but extremely popular in sediment transport in open channel flows.

A similar force balance approach for pipe flows was developed by Wicks (1971) who studied the transportation of low concentration solids in horizontal pipes. Plexiglas pipes 7.5 and 11-m long with 0.0254 and 0.1397 m IDs respectively were used in the study. The test was conducted by first developing a sand bed in the pipe through entrainment before injecting liquid into the line till a velocity is reached where all the sand particles in the bed became entrained in the flow, the experimental critical velocity was thus obtained for each point by considering the limiting flow velocity with zero bed height. A comparative study was done on existing models notably Durand (1953) and Hughmark (1961) with huge discrepancies observed. Wicks proposed a model based on force analysis on the sand particle in the sand bed, four main forces namely the buoyant, $\boldsymbol{F_B}$ gravity, $\boldsymbol{F_G}$, lift, $\boldsymbol{F_L}$ and drag, $\boldsymbol{F_D}$ forces were considered (Figure 1).

For motion of the particle that rests on two other particles to occur, force moments about point (*x*, *y*) that tends to cause downstream particle rotation must be greater than that which tends to resist this rotation, this was expressed mathematically as:

$$\boldsymbol{F_B} + \boldsymbol{F_L} + s\boldsymbol{F_D} > \boldsymbol{F_G} \tag{1}$$

where $s(= y/x)$ is the shape factor. Appropriate expressions for the terms in the above equations were determined by evaluating their dependence on flow parameters. The condition for incipient motion of particles yielded a final form thus:

$$S \times \Psi = 1 \tag{2}$$

where; $S = (C_D + 1.44C_L)\phi/8$ and $\Psi = \rho_l^3 d_p V_s{}^4/(\rho_P - \rho_l)g\mu_l^2$. C_D and C_L are drag and lift coefficient respectively, and ϕ is a function of the Reynolds number and d_p/D. V_s is the average flow velocity above the sand bed. Wicks further proposed a dimensionless group thus:

$$\mathrm{S} = \frac{D_{EQ}\rho_l V_s}{\mu_l^2}\left(\frac{d_p}{D}\right)^{2/3} \tag{3}$$

$D_{EQ}(= 4A_L/S_L)$ is the hydraulic equivalent diameter, A_L and S_L is the pipe's cross-sectional area and wetted perimeter occupied by liquid respectively.

From experimental data obtained in his study, Wicks plotted S versus Ψ in a Log-Log diagram and obtained the relation:

$$\Psi = \begin{cases} 0.1S^3 & S < 40 \\ 0.1S^{3/2} & S > 40 \end{cases} \tag{4}$$

Turian *et al.* (1987) used 864 experimental critical velocity (defined as the minimum velocity demarcating flows in which the solids form a bed at the bottom of the pipe from fully suspended flows) data published in literature for various conditions to develop a correlation. By recasting several correlations in literature into a standard form and assuming a uniformly sized spherical particles, smooth pipe walls and a gravity effect $[(\rho_s - \rho)g]$, viewed as a form of particles net settling forces, they proposed thus:

$$V_c = f[d, D, C, (\rho_s - \rho)g, \rho, \mu] \tag{5}$$

Using the dependence of critical velocity on $D^{1/2}$, the equation was written in non-dimensional variable form with a reference velocity, $[2gD(s-1)]^{0.5}$, thus:

$$\frac{V_c}{[2gD(s-1)]^{0.5}} = f\left[\left(\frac{d}{D}\right), \frac{D\rho[gD(s-1)]^{0.5}}{\mu}, C\right] \tag{6}$$

The final form of the model was proposed thus;

$$\frac{V_c}{[2gD(s-1)]^{0.5}} = X_1 C^{X_2}(1-C)^{X_3} C_D^{-0.0272}\left\{\frac{D\rho[gD(s-1)]^{0.5}}{\mu}\right\}^{X4}\left(\frac{d}{D}\right)^{X_5} \tag{7}$$

where C_D is the drag coefficient of falling sand particles given by $C_D = (4/3)gd(s-1)/v_{sl}^2$. The equation was considered in various forms for various adjustable constants, X_i by fitting 864 critical velocity data using of multi-linear regression in which the logarithmic forms were fitted. Values for X_1–X_5 that gave the least root mean square error were [1.795, 0.1084, 0.250, 0.0018, 0.0662] respectively. The study concluded that critical velocity is dependent on pipe diameter by about $\sqrt{D}$, weakly dependent on particle diameter, d ($\approx d^{0.06}$) and that a maximum exist at in the V_c vs C relationship, maximum V_c occur at C between 0.25 and 0.30.

Davies (1987) using deductions from turbulence theory and a correction factor for eddy damping developed a theoretical model for the critical velocity, V_c, in horizontal pipelines. In this model, V_c is defined as the minimum mean flow velocity required to suspend particles in horizontal pipe flow. The model developed is similar to the Durand and Condolios (1952) relation but their exponents were close to those in the empirical correlation of Oroskar and Turian (1980). It also shows a greater dependence on the solid particle diameter, d_p and explains the observed maxima in F_1 (dimensionless term which depends on particle diameter and the average solids concentration, c) at $c = 15\%$. In developing the model, the sedimentation force of the particles and the force of the turbulent eddy were considered. At a point when all the particles in the pipe are just being suspended in the liquid by eddies, the sedimentation force equals the eddy force.

$$\frac{\pi}{6}d_p^3\Delta\rho g(1-c^n) = \rho_l(v')^2\left(\frac{\pi}{6}d_p^3\right) \tag{8}$$

$\Delta\rho$ is the difference in density between particles and liquid, g is the gravitational acceleration, ρ_l is the density of liquid, n is the exponent of hindered settling and v' is the eddy fluctuation velocity. From equation above, the eddy fluctuation velocity is obtained as:

$$v' = 0.82(1-c)^{n/2}d_p^{1/2}[g\,\Delta\rho/\rho_l]^{1/2} \tag{9}$$

The final step in the model involves the relating v' and V_c. Davies stated that since the larger eddies were unable to approach the bottom of the pipe where some of the particles settled and the smaller eddies were unable to lift the particles, eddies of interest were roughly the same length as the particles' diameter, d_p. For fluid void of solids, Davies gave the eddies velocities as;

$$(v')^3 = P_M d_p \tag{10}$$

P_M is the power dissipated per unit mass of fluid and is given by:

$$P_M = 2fv_m^3/D = 0.16v^{1/4}{V_c}^{2.75}D^{-5/4} \tag{11}$$

f $(= 0.08/Re^{1/4})$ was considered as the fanning friction factor. Re is the Reynolds number. Thus the eddy velocity becomes:

$$v' = (0.16)^{1/3}V^{1/12}{V_c}^{0.92}D^{-0.42} \tag{12}$$

Davies introduce a turbulence correction factor which reduces the turbulence eddy velocity $(v'/(1+\alpha c))$ to cater for the solids which when introduced to the system will dissipate some of the turbulent eddies and equated the eddy and sediment velocities to obtain the equation,

$$V_c = 1.08(1+\alpha c)^{1.09}(1-c)^{0.55n}V^{-0.09}d_p^{0.18}[2g\Delta\rho/\rho_l]^{0.54}D^{0.46} \tag{13}$$

Oudeman (1993) used the general relation between fluid mechanical parameters and sediment transport to study sand transport in multiphase pipelines. Two dimensional quantities were used to describe the sediment transport and the fluid flow rates. A power law was subsequently used to relate both quantities. The drag velocity was obtained from the mixture velocity by assuming a logarithmic profile at the boundary layer.

$$\phi = \frac{S}{\left(\sqrt{{d_p}^3(g(F-1)}\right)} \tag{14}$$

$$\psi = \frac{{v_b}^2}{\left(gd_p(F-1)\right)} \tag{15}$$

The model was proposed thus:

$$\phi = m\psi^n \tag{16}$$

where F is the transport rate in grain volume per second per meter of sand bed width, ϕ is the dimensionless sand transport rate, ψ is the dimensionless fluid flow rate, d_p is the solid particle diameter, g is the gravitational acceleration, S is the solid-liquid density ratio and v_b is the drag velocity in sand bed, while *m* and *n* are constants that depend on input gas fractions.

Literature survey

Durand and Condolios (1952) proposed a correlation for the critical velocity (defined as the velocity at which particles are transported without forming a bed at the bottom of the pipe and minimal head loss (necessary to optimise slurry transport). The correlation was developed from experimental investigations conducted with sand, gravel and coal with particles' size range of 0.05–25 mm and pipes with IDs of 0.038–0.711 m, and maximum sand concentration by volume of 0.15 % v/v was used. Concentration, pipe diameter, particle size, solid and liquid density were investigated and used in developing a correlation. The critical velocity, V_c was proposed thus:

$$V_c = F_{Durand}\sqrt{[2gD(s-1)]} \tag{17}$$

where F_{Durand} is the Durand coefficient which is a function of sand concentraton. It is obtained from empirical chart the author proposed. The parameter s is the solid to liquid density ratio.

A correlation was proposed by Hanks (1980) for the minimum deposit velocity is given as $V_c = 1.32\phi^{0.186}[2gD(s-1)]^{0.5}(d/D)^{1.6}$ where s is the density ratio of the sand particles to that of the liquid, and ϕ is the sand volume fraction. At velocities below V_C the solids settle out in a bed along the bottom of the pipe, which can accumulate and plug the pipe if the velocity is too low. Furthermore, it can be swept along the pipe wall if the velocity is close to the minimum deposit velocity. Above the minimum deposit velocity, the particles are suspended but are not uniformly distributed until turbulent mixing is high enough to surpass the settling forces. A criterion for non-settling suspensions was given by Wasp et al. (1977) as $V_t/V^* \leq 0.022$, where V_t is the particle terminal velocity and $V^*=\sqrt{\tau/\rho}$ is the friction velocity.

Charles (1970) developed a critical velocity correlation which he defined as the velocity at which solid particles are deposited at the bottom of the pipe. Charles used the fact that the minimum pressure gradient corresponds to the velocity at which particles begin to deposit. He proposed a correlation thus:

$$V_C = \frac{4.80{C_V}^{1/3}[gD(s-1)]^{1/2}}{C_D^{1/4}[C_V(s-1)+1]^{1/3}} \tag{18}$$

where s is the ratio between particle and fluid density and the drag coefficient, $C_D = 4gd_P(s-1)/3V_t^2$. Thomas (1962) proposed a model to determine the minimum transport condition, MTC – “defined as the minimum velocity demarcating flows in which sand form a bed at the bottom of the pipe from fully suspended flows”. The model was developed by considering two key factors that affects suspended particles distribution in flow streams: thickness of the laminar sub layer, buffer & turbulent core and the ratio of the terminal settling velocity to the friction velocity. Reynolds Number and the factors considered were used to develop a particle flow pattern map which was divided into two main regimes to account for MTC: Flow in which the particles are mostly in suspension and its diameter is smaller than the viscous sub layer, and which obeys Stokes’ law in settling. $V_t/V_o = 0.2$ was the transition point for particles transport, in heterogeneous suspension $V_t/V_o > 0.2$ or forming a stationary bed

$V_t/V_o < 0.2$. Thomas subsequently developed a correlation based on previous works using dimensional analysis. For particle smaller than the viscous sub layer thickness, the friction velocity at deposition for infinite dilution (single particle) is given by:

$$V_o^* = \left(100 w_s \left(\frac{v}{d}\right)^{2.71}\right)^{0.269} \tag{19}$$

For particles greater than the laminar sub layer thickness, V_O^* is given by:

$$V_o^* = \left(0.204 w_s \left(\frac{v}{d}\right)\left(\frac{v}{D}\right)^{-0.6}\left[\frac{\rho_S - \rho_l}{\rho_l}\right]^{-0.23}\right)^{0.714} \tag{20}$$

If large concentrations of particles (with diameter in excess of boundary layer thickness) are in the system, the infinite dilution value is modified to account for other particles thus;

$$V_c^* = V_o^*\left[1 + 2.8\left(\frac{w_s}{V_o^*}\right)^{0.33}\sqrt{\Phi}\right] \tag{21}$$

w_s is the particle settling velocity in laminar flow condition and v the kinematic viscosity. D and d are the pipe and particle diameters while ρ_S and ρ_l are the solid and liquid density respectively. Φ is the particles solid volume fraction in the slurry. The laminar sub layer thickness, $\delta = 62D(V_{sl}\rho_l/\mu_l)^{-7/8}$. In using the model, prediction of either V_c^* or V_o^* as function of flow velocity is required.

Extending Thomas' correlation at infinite dilution (i.e. Equation 3), Fajemidupe et al. (2019) included the effect sand concentration by correlating MTC data from a 2-inch horizontal pipeline. Sand velocities were obtained by cross-correlating signals from an adapted conductance probe previously used by Aliyu et al. (2017) for liquid film thickness measurements. They showed that at particle concentrations as low as 0.1%, the MTC can be well predicted by a relationship which has a second power law term to account for particle concentration.

From literature review of sand transport models, it is observed that many models exist for predicting the critical velocity of sand in horizontal pipelines. However, none of these existing models took into consideration the effects of pipeline inclination. Roco (1977) studied sand transport in water flow with pipeline inclination ranging from -25° to 30°. A 0.10-m ID pipe was used in the study with sand particle size of 360 microns. The work showed gradual increase in critical velocity values from -25° to about +15° after which the critical velocity decreased as pipe inclination angle increased from +20° degrees to +30°. Additionally, Angelsen et al. (1989), Rix & Wilkinson (1991), Danielson (2007) and Yan (2010) all concluded from experimental investigations in their study that the critical velocity increased with increase in pipe inclination albeit, not by a large magnitude.

The present study is focussed on experimental investigation of two-phase sand-water flow in a horizontal and 30° upward inclined pipes with IDs of 0.0254 m. Sand transport models in literature will be evaluated against experimental data and the best performing model will be identified. One of the key factors in the design of fluid flow through conduits is the pressure ratings of such system; this is particularly so in two-phase solids-liquid flows. Pressure measurements are directly responsible for the pumping requirements, mechanical integrity and safe operations of slurry systems. However, the study of slurry behaviour in pipes has largely depended on empirical correlations and this is not surprising because the components of practical slurries vary in physical composition and properties. Few studies exist in literature where pressure gradient were investigated in pipeline slurry flows, for example, Newitt et al. (1955) reported that the contribution of the solid phase to the frictional loss in the pipe flow is the result of the particles immersed weight being transported to the pipe wall. Charles and Charles (1971) transported fine sand particles in shear thinning clay suspensions and reported head loss which was six times smaller compared to the result gotten when water was used as the carrier fluid. Gillies and Shook (1994) reported a reduction in pressure gradient when a shear thinning Carboxymethyl Cellulose (CMC) solution was used to transport fine sand particles, but not for larger pea gravel particles; this was attributed to the fact that these larger particles were conveyed in the form of a sliding bed and not as a suspension. In this study, we will measure the pressure gradient obtained and analyse their characteristic trend.

Experimental Setup

Test Facility

The flow loop used in the experimental investigation of this study shown in Figure 2 is a 0.0254-m internal pipe diameter facility that is inclinable to the horizontal from 0°–30°. The pipe section is 5.5 m long in the horizontal section while the 30° upward inclined section is 8.0 m in length. Measuring instruments were placed at least 60 pipe diameters from the flow injection into the test line while observations and measurements were obtained at 100 pipe diameters. The observation and measurement points were decided on the basis preliminary experimental observations were flow developments was studied in the test facility. Pipe material used in the study was Perspex, with pipe thickness of about 3 mm.

The water and sand mixture (also referred to as slurry) system consists of a 0.2 m^3 cylindrical plastic vessel; maximum volume by volume fraction for the facility is 15%. For each experimental test run, the weight of sand equivalent to the volume fraction is added to the water in the tank while an axial flow impeller with twin blades placed about 0.3 m above the vessel's conical base is used to stir the slurry (water and sand) mixture to ensure homogeneity. The conical base opens into the slurry pump, a progressive cavity pump with maximum flowrate 2.18 m^3/hr and absolute discharge pressure of 10 bar. The PCP pumps the slurry into the test line via a Promag 55S50, DN50 electromagnetic flowmeter with maximum flowrate of 2.18 m^3/hr. A 4–20 mA HART output is connected to a data acquisition system for logging.

GE Druck pressure transducers, PMP 1400, with pressure range 0 – 70 mbar and 0 – 200 mbar with accuracies of 0.04% over the full scale were used to obtain the in situ pressures in the test line while a differential pressure transducer, Honeywell STD120, with minimum pressure drop measurement of 100 Pa and an accuracy of ±0.05% (of full scale) is used to measure the differential pressure. Temperature of the test fluids on the test section is measured by means of J-type thermal couples with accuracy of ±0.1°C placed at different locations.

Data acquired from the flowmeters, differential pressure transducers, pressure transducers and temperature sensors are saved to a Desktop Computer using a LabVIEW® version 8.6.1 based system. The system consists of a National Instruments (NI) USB-6210 connector board interfaces which output signals from the instrumentation using BNC coaxial cables and the desktop computer. Three Sony camcorders, DSCH9 with 16 megapixels, high definition and 60GB HDD are used for video recordings during the test to aid visual observations.

Test Materials

The test materials which comprises of the solids and fluids used in this study will be discussed here in terms of their physical properties. These physical properties are essential in aiding the understanding of multiphase flow characteristics. They are also an important input parameter in predictive models and correlations.

Test Fluid and Solids

Water used was from the mains supply, its viscosity and density of 0.001 Pa.s and 998 kg/m^3 at 20°C. The sand particles in this study are the Congleston HST 95 with manufacturer's specification stating a density of 2650 kg/m^3 and mean particle size of 150 microns is used. The d_{10}, d_{50} and d_{95} of the sand particles were 100, 144 and 210 microns respectively.

Particle Size Analysis

Particle size distribution analysis using sieve techniques was conducted before being used in the experiments in order to determine the mean sand size (Figure 3). In the sieve analysis, sand from a particular sample is weighed and passed through sieves (screens) of decreasing sizes.

The screens are then mounted on the sieve shakers where horizontal and vertical motion is imparted to the sieves to enhance particles movement. The number of particles remaining in each sieve is weighed and subtracted from the weight of the empty sieve; these results are subsequently used in particle size distribution analysis. Results can be presented in discrete sequential size range or in cumulative terms based on a predefined upper and lower-class boundary class for the particle size. In this study, the Congleston HST 95 with manufacturer's specification stating a density of 2650 kg/m^3 and mean particle size of 150 microns is used. The sand size analysis from laboratory work is shown in Figure 3.

Test Matrix

Table 1 (a) shows the test matrix for the flow range covered in the horizontal and inclined test section. For both inclinations, the mixture velocity was varied from 0.2 to 1.2 m/s. On the other hand, sand concentrations used were different, for the horizontal pipe concentrations were 0.0025 to 0.1 v/v while for the 30^o inclined pipe, the concentrations were lower at between 0.001 to 0.05 v/v. The literature of sand transport in pipes usually has sand concentrations frequently given in imperial units of pounds of sand per 1000 barrels (i.e. lb/1000bbl). As a result, and to facilitate comparison with our data, the second part of Table 1 shows the sand concentrations in equivalent volume per volume percentage (% v/v) units. The conversion factor given as follows: C_v [in % v/v] = C_v [in lb/1000 bbl]/9.27×10^5.

Experimental Procedure

Before each experimental run, settled sand within the test section is purged by pumping water into the flow line and ensuring the inlet sand valve is firmly shut. Sand-water mixture of required concentration is prepared in the sand mixing tank. Before injecting sand-water mixture into the test line, the sand-liquid composition was mixed thoroughly and introduced into the horizontal test section via a 0.25-inch flexible pipe that connects the sand injection pump to the test section. Video recordings were taken once the flow is adjudged to reach equilibrium. Pressure and flow rate readings are automatically logged via a LabVIEW system. The liquid flow rate is gradually decreased to achieve the minimum transport conditions (MTCs) at different sand concentrations.

Results and Discussion

We consider two categories of sand loading (by volume per volume fraction of sand in water): low sand loading with concentrations <1% v/v and higher sand concentrations ≥ 1% v/v. The effect of inclination is analysed by using experimental results obtained from the horizontal and 30° inclined orientations. Furthermore, comparisons will be made of the experimental MTCs and pressure gradients with published models in the open literature.

Flow visualisation of sand transport characteristics

Seven sand concentrations in both test orientations were observed with the aid of two camcorders. Both cameras were placed about 20–30 cm from the viewing sections in the side and bottom positions to ensure flow features of sand particulates from the side and bottom views are clearly captured.

Characteristics in Horizontal Test Section

Table 2 shows representative results of the flow patterns for 1% v/v sand concentration experiments. Deposition test is conducted in water-sand transport study; the test involves the gradual reduction of the injected slurry (water-sand mixture) from the highest velocity to the lowest. Video recordings and instantaneous pressure gradient data acquisition is obtained for each test point. Images below were obtained from videos recorded at selected test condition. For clarity, the key forces that govern particles transport in fluids are: gravity, buoyancy, lift and drag; with gravity being the key opposing force to particle suspension in flow. Gravity force remains constant for a particular sand particle size and concentration. Drag force acts in the horizontal direction and opposes the relative motion of the fluid flow. Buoyancy and lift forces which vary proportionally with the square of the fluid velocities however acts to keep the particle in suspension.

At 1% v/v sand concentration and slurry velocity of about 1.20 – 1.0 m/s, a *homogenous suspension* of sand particles in the flow stream was observed. In this flow pattern, the lift and buoyancy forces dominate the gravity force hence keeping the sand particles in suspension; their dominance is due to high flow velocity. sand particles were completely suspended (dispersed) in the carrier fluid (water) and distributed in *homogenously* in the pipe's cross section. This flow pattern termed the *Dispersed Flow* is always a problem to industrial operators due to its high frictional pressure drop and hence high power consumption and its ability to cause erosion in the pipe for low viscosity liquid flows.

When slurry velocity was reduced to below 1.0 m/s, lift and drag forces gradually lose their dominance (both depends on the mean flow velocity) while gravity forces which is unchanged gradually begins to gain some prominence as a result. Sand particles are still fully suspended in flow; however, they were observed to be *heterogeneously dispersed.* Here, most of the particles flow near the pipe's bottom due to gravity effect, however, they are observed to be still in suspension.

At velocity of about 0.87 m/s, the sand characteristic behaviour observed termed; *sand streaks.* Here, the onset of sand particle deposition is observed with sand streaks being formed at the pipe's bottom centreline. An increase in the streak thickness was observed on further reducing the slurry velocity to 0.70 m/s. This velocity range was noted as the Minimum Transport Condition (MTC). Below the MTC, at a velocity of about 0.6 m/s, a moving sand bed was observed in the pipe bottom and the bed became denser on further reduction of slurry velocity.

This flow pattern was termed *Moving Sand Bed Flow*. A subsequent reduction to 0.4 m/s saw the formation of stationary sand bed with the bed getting thicker as slurry velocity reduced. The flow pattern was termed *Static Sand Bed*.

A reduction of slurry velocity to 0.3 m/s saw the emergence of a new flow pattern termed *Moving Dunes;* in this flow pattern, sand particles were observed to separate from static sand bed in to dune-like colonies. The particles at the tail of the moving dunes saltate into the sheltered region separating one dune body from another and remained almost immobile until its parent dune travelled down and engulfed it. The settling of particles at the bottom of the pipe at this relatively low velocity indicates the dominance of the gravity forces which acts to oppose sand suspension in flow.

Characteristics in Inclined Test Section

Sand transport characteristics observed in the inclined pipe section was similar to those in the horizontal experiments; *Dispersed, Sand Streaks, Moving Sand Bed, Static Sand Bed* and *Moving Dunes flow patterns*. Representative results obtained for 0.5 and 1.0% sand concentrations are shown in the lower part of Figure 4. For the low sand loading with sand concentration of 0.5% v/v, sand dunes were not observed, this may be as a result of the relatively lower sand fraction which makes the dune formation harder to establish.

Sand Minimum transport conditions (MTC) in horizontal and inclined orientations, correlational analysis

Before going into the results and detailed comparison with selected prediction models earlier outlined in the introduction, it is important to differentiate between the two classes of MTC correlations in the literature. The first class directly correlates the minimum transport velocity V_{MTC} with dimensionless numbers characterising the fluid properties and flow conditions. Examples are the correlations of Oroskar and Turian (1980), Al-Mutahar (2006) and Wasp et al. (1970). The second class does not correlate V_{MTC} directly but correlates a friction velocity obtained by non-dimensionalising V_{MTC} with the fluids mixture shear stress. Authors such as Thomas (1962), Yan (2010), Fajemidupe (2016) and Fajemidupe et al. (2019) used this methodology. However, this method is highly dependent on accurate measurement of the shear stress instead of only observations of initial sand transport. As a result of this added complexity of the second method, here we examine the prediction performance of the first class of correlations.

Minimum transport velocity

Thomas (1962) defined MTC as “the minimum velocity demarcating flows in which the sand form a bed at the bottom of the pipe from fully suspended flows”. This definition was used as the basis for qualitatively determining the MTC at different sand concentration. It was generally observed that the MTC value increased with increase in sand concentration.

Within the scope of this study, MTC observed were seen to increase with increase in sand concentration. This is attributed to gravity forces which increase with increase in sand concentration. Studies by Durand & Condolios (1952), Sinclair (1952) and Wasp *et al*. (1970) that account for volume fractions concentration all indicates an increase in the predicted minimum transport conditions with increase in sand concentration. Table 3 shows the MTC obtained in this study at different sand concentration. As earlier stated, gravity forces act to oppose the suspension of sand in flow. When sand concentration is increased, the gravity forces increases; this is because the force is directly proportional to mass (of sand).

Minimum transport condition was visually obtained by analysing the video recordings taken for each sand concentration within the test matrix studied. It was observed as shown in Table 2 that for a fixed sand concentration, the minimum velocity required to transport sand was slightly lower in the 30° inclined pipe section compared to the horizontal test section.

Several researchers such as Angelsen *et al*. (1989), Shook and Roco (1991), Rix & Wilkinson (1991), Danielson (2007) and Yan (2010) concluded from experimental investigations (limited to inclination angle of 15° from the horizontal) in their study that MTC increased slightly when pipeline was inclined. Roco (1977) concluded that for pipe inclinations above 15°, MTC reduced compared to corresponding conditions in the horizontal orientation. The slight decrease in MTC as the pipeline inclination increases may be attributable to the relatively reduced interactions between sand particles and the friction between pipe walls and sand as these are major factors that affect sand transport (Yan, 2010). It is also worth noting that by inclining the pipeline, the gravity force which hitherto acted normally to the pipeline will have a component acting parallel to the inclined pipe section.

Figure 5 shows that the Durand and Condolios (1952) correlation performed well even at sand concentrations below 1%. Table 3 statistically corroborates this as the best performing correlation among those surveyed going by values of the MSE of 0.00140 and PMAE of 3.5% which are the best among the surveyed correlations. The next best performing is the Oroskar and Turian (1980) correlation which produced values of MSE and PMAE of 20.8 and 0.01895 respectively, a distant second when compared to the performance of Durand and Condolios (1952). Furthermore, 100% of its data points were within ±20% of the horizontal experimental data, while for Oroskar and Turian, only a third of its points were within ±20% of the experiments. On the other hand, Durand and Condolios's correlation is restricted because of its reliance of on the Durand chart, this chart is limited to concentrations below 1% and above 15%. The Wasp et al. (1970) correlation under-predicted the MTC value for all the sand concentration in this study. Davies (1987) and Danielson (2007) predicted and unchanged MTC for all the sand concentration, this is as a result of their models' neglect of the sand concentration as input variable. Turian et al's (1987) correlation grossly under-predicted all the MTC in this study with deviations of up to an order of magnitude for similar conditions when compared with our experimental measurements and the predictions of other models such as those of Durand and Condolios (1952) and Oroskar and Turian (1980) which gave predictions closer to the experiments. As can be qualitatively seen from Figure 3, and confirmed by the statistical values in Table 3, all the other correlations were vastly superior. A reason for these performances could be attributed to the lack of consideration for viscous effects on sand transport as well as limited experimental ranges considered for the model developments. Regarding the trend of VMTC for the inclined section when compared to that of the horizontal orientation, deviations only start to manifest at sand concentrations beyond 1%, but even so, these deviations were less than 1% of the experimental. As a result, the correlation of Durand and Condolios can be used within this range of sand concentration.

In summary, one can say that from the comparisons above, based on Figure 4 and Table 4, the relationship of Durand and Condolios (1952) provided the most accurate predictions in terms of both magnitude and trend when compared with our experimental measurements of the MTC at different sand concentrations and flow velocities.

Correlation of sand MTC taking account of pipe inclination

In the previous section, inadequacies have been identified of reported correlations in predicting sand MTC in a wide variety of sand particle concentration, size and pipe inclinations. Therefore, it is imperative to find a relationship that adequately incorporates the effect of these variables including those at very low and high particle concentrations and indeed negative pipe inclination (downward inclined). In this section we attempt to do that. A databank of sand–water studies was collected which consists of 181 MTC data points from includes of 9 different investigations including the current horizontal and vertical experimental points.

The features of the data in the collected databank are summarised in Table 4. As can be seen in the table, most of the studies were conducted in horizontal pipes of small diameter (<0.1 m). However, among the pipes Oroskar and Turian (1980) and Parzonka et al. (1980) obtained their measurements are larger diameter pipes of up to 0.7 and 0.4 m respectively. Most of the collected studies used pipes in a horizontal orientation. Conversely, nearly half of the data points comprised of flows in inclined pipes and these are from the current study (at 30° inclination) and those of Roco (1977) at various inclinations ranging from -25° to 30° in increments of 5°. Regarding sand particle sizes, there was a wide variety. Many of the authors used irregular sand particles of mean size less than 500 µm. However, Oroskar and Turian

(1980) and Parzonka et al. (1981) used more coarse particles with mean size of up to 2,000 μm and as expected, these produced the highest critical velocities in the databank.

For developing a new correlation that incorporates both sand concentration and pipe inclination, we tested several correlational forms, and refer to the correlating method of Turian *et al.* (1987), which worked best with our collected database. Turian and co-workers formulated the critical velocity as depending on the pipe and particle diameter, particle concentration, densities, and fluid viscosity; and after dimensional analysis they arrived at the relationship described in Equation (12). For pipe inclination effect, we add to that equation, a power law function using $(1 - cos\theta)$ as follows:

$$\frac{V_c}{[2gD(s-1)]^{0.5}} = X_1 C^{X_2} (1-C)^{X_3} C_D^{-0.0272} \left\{\frac{D\rho[gD(s-1)]^{0.5}}{\mu}\right\}^{X4} \left(\frac{d}{D}\right)^{X_5} + X_6 (1-cos\theta)^{\ X_7} \tag{22}$$

where C_D is the sand particle drag coefficient given by $C_D = (4/3)gd(s-1)/v_{sl}^2$. For horizontal pipes, $(1 - cos\theta)$ results in zero and the predicted critical velocity is given by a final form of Equation (12). Using the 181 data points collected and represented in Table 4, the coefficients and indices $X_1 - X_7$ were obtained using nonlinear least squares regression with the aid of the solver function in Microsoft Excel. The final correlation obtained is:

$$\frac{V_c}{[2gD(s-1)]^{0.5}} = 2\ C_v^{0.23} (1-C_v)^{0.10} C_D^{-0.0272} \left\{\frac{D\rho[gD(s-1)]^{0.5}}{\mu}\right\}^{0.05} \left(\frac{d}{D}\right)^{0.12} + 0.07(1-cos\theta)^{\ 0.59} \tag{23}$$

As shown in Figure 6, most of the predictions of Equation (23) agree with the experimental database and are within a ±20% error margin. Notable deviations from this correlation are shown in the figure as indicated with the arrows, they correspond to the pipe inclinations of -25°, -20°, and -15° all at high sand loading i.e. $C_v = 0.4$ v/v for the data of Roco (1977). It thus appears to signify that downward inclining flow dynamics from -15° are entirely different to those of upward inclining and horizontal pipes at 40% particle loading. A possible reason for this behaviour is the additional effect of gravitational force now having a component in the direction of flow. Further studies with full mechanistic modelling may be needed to fully account for downward incline critical velocity deviations.

Pressure gradient of sand flow in horizontal and inclined orientations

A key parameter used by engineers in the design of pipeline for slurry systems is the pressure gradient; it also gives an indication of the power requirements for the transport of slurry. In this work, pressure gradients were measured by means of a differential pressure transducer.

Pressure gradient obtained in the study are illustrated in the plots of Figure 7 (a) where pressure gradient is presented as a function of slurry (water/sand) velocity. The effect of sand concentration on the pressure gradient is seemingly prominent with increase in sand concentration. At a lower sand concentration of 1%, pressure gradient is observed to be similar and with a near-match of the single-phase pressure gradient line differing slightly in the lower slurry velocities due to the settled sand bed. The model proposed by Gilles and Shook (2000) lays credence to this behaviour; since sand bed is non-existent at the higher slurry velocities, all the suspended particles contributes to the kinetic stresses which serve largely as the only source of friction loss and hence pressure gradient similarity for single phase water and two-phase water-sand flows. At reduced slurry mixture velocity, the shear forces on the pipe walls and the kinetic stresses on the upper boundary layer increases as sand beds begin to form. This results in an increase in the pressure gradient in the pipe, for a relatively lower sand concentration, the deviation of the line from the single-phase pressure gradient line is slight; this is due to the thin size of the bed formed.

At higher sand concentrations (10% v/v), the sand bed formed in the pipeline is stationary, hence resulting in low friction with the pipe wall resulting in lower and lower pressure gradient until a minimum is reached. At MTC when the sand bed begins to move, there is increased friction with the pipe wall resulting in increasing losses as the mixture velocity is increased. The pressure gradient increases sharply as a result of this as is shown in both Figure 7 (a) for the horizontal and (b) for the inclined condition. Furthermore, the pressure gradient in the inclined pipe at low sand concentrations is proportional to the slurry mixture velocity, just as in the horizontal section. However, their magnitudes were observed to be higher than that of the horizontal section; this is attributed to gravity effect in the inclined section. Essentially, in inclined flows, the pumping requirements are much higher and the pressure gradient required to drive the fluid uphill thus becomes larger due to the existence of a gravitational component in the flow direction retarding the mixture transport.

Comparison of experimental and predicted pressure gradient

Figure 8 shows a comparison between the present study and predictive pressure gradient correlations for slurry flow in literature. The correlations that were employed show relatively good agreement with the present results for 0.2% up to 1% sand concentration. All the models over-predicted the gradients at high sand concentration (>1% sand concentration). The best performing model was observed to be the Durand and Condolios (1952) model. These discrepancies in prediction may be due to the inconsistencies of the MTC correlation that were used to predict the determinant variable which influenced the output of the pressure gradient correlations. This could also be justified by the fact that different correlations evolved from different slurry compositions and other parameters like pipe diameter, pipe material etc.

Conclusion

Two-phase slurry flow with sand concentration ranging from 0.2 to 10% and 0.1 to 5% sand concentration was studied in the horizontal and inclined pipeline sections respectively. Visual analysis of flow patterns from video recordings obtained during experiments were made for both pipe sections. *Disperse* (heterogeneous and homogenous), *Sand Streak*, *Moving Bed*, *Stationary Bed* and *Sand Dunes* were observed, MTC values were observed to increase with increased sand concentration for both sections while they reduced slightly when pipeline orientation changed from horizontal to 30° upward inclination to the horizontal. Of the MTC correlations/models evaluated, the Durand and Condolios (1952) model gave the best prediction above 1% sand concentration. It also gave the best general prediction of the entire MTC trend studied. For pipeline design of flow lines and in sand management strategic plans, it may be useful to implement the Turian et al. (1987) model's prediction with a conservative design factor margin. Pressure gradient analysis was also presented; it was observed that the pressure gradient behaviour for low sand concentration (≤1%) was different from that of high sand concentration (>1%). While pressure gradient reduced with a reduction in mean slurry velocities for the lower sand concentration range, it was observed that at the higher sand concentration range, the minimum pressure gradient was observed close to the MTC. Beyond the minimum, pressure gradient increased with a further reduction in slurry velocity. A previously reported dimensionless relationship was modified to now include the effect of pipe inclination. Extensive literature data in addition to the current measurements were used such that the effect of key flow, geometric and particle parameters were adequately captured by the new correlation. Against the available data, it produced an improved performance for sand minimum transport conditions in horizontal and inclined pipes.

Acknowledgement

The first author (AAE) received funding from the Oil and Gas Engineering Centre; Cranfield University, for his doctoral studies. The 3rd and 4th authors (AMA and YDB) received funding from the Nigerian Government for their PhDs in the UK through the Petroleum Technology Development Fund's Overseas Scholarship Scheme (PTDF/E/OSS/PHD/AMA/622/12 and PTDF/E/OSS/PHD/BYD/532/12).

Notation

Symbol	Description	*Units*
a. Roman letters		
C_v	Particle volume concentration	*v/v*
D	Inside pipe diameter	m

d_p	Particle diameter	m
f	3-phase friction factor	-
g	Acceleration due to gravity	m/s^2
H_g	Gas hold-up	-
H_l	Liquid hold-up	-
L	Pipe length	m
P	Pressure	bar
$u_p, u_{p,c}$	Particle velocity, subscript c denotes critical	m/s
u_c^*	Friction velocity	m/s
V_L	Actual liquid velocity	m/s
V_{mix}	Mixture velocity	m/s
V_{sg}	Gas superficial velocity	m/s
$V_{sg,c}$	Critical gas superficial velocity	m/s
V_{sl}	Liquid superficial velocity	m/s

b. Greek Letters

δ	Boundary layer thickness	m
ε	Pipe wall roughness	–
ρ	Fluid density	kg/m^3
ρ_G	Gas density	kg/m^3
ρ_L	Liquid density	kg/m^3
ρ_P	Particle density	kg/m^3
μ	Fluid viscosity	$Pa \cdot s$
μ_g	Gas viscosity	$Pa \cdot s$
μ_L	Liquid viscosity	$Pa \cdot s$
μ_m	Viscosity of flow mixture	$Pa \cdot s$

References

Al-Mutahar, Faisal, (2006), "Modeling of Critical Deposition Velocity of Sand in Horizontal and Inclined Pipes", MSc Thesis, Department of Mechanical Engineering, the University of Tulsa, Tulsa.

Aliyu, A.M., Almabrok, A.A., Baba, Y.D., Archibong, A.-E., Lao, L., Yeung, H., Kim, K.C., (2017). Prediction of entrained droplet fraction in co-current annular gas–liquid flow in vertical pipes. Exp. Therm. Fluid Sci. vol. 85, pp 287-304. http://dx.doi.org/10.1016/j.expthermflusci.2017.03.012.

Angelsen, S., Kvernvold, O., Lingelem, M., Olsen, S., (1989), "Long-Distance Transport of Unprocessed HC Sand Settling in Multiphase Pipelines", Proceedings of The Fourth International Conference on Multiphase Flow, Nice, France, June, pp.19-21.

Archibong, A. (2015), High Viscous Multiphase Flow Characteristics in Pipelines. PhD Thesis. Cranfield University, United Kingdom.

Archibong A., Yan W., Baba Y, Kanshio S, Yeung H. (2015). Viscous Liquid-Gas Flow in Horizontal Pipelines: Experiments and Multiphase Flow Simulator Assessment. 17th International Conference on Multiphase Production Technology, 2015

Archibong-Eso, A., Baba Y., Aliyu, A, Zhao, Y., Yan W., Yeung, H. (2018). “On Slug Frequency in Concurrent High Viscosity Liquid and Gas Flow”. Journal of Petroleum Science and Engineering. 163, 600-610, 2018

Archibong-Eso, A., Baba Y., Aliyu, A, Okeke, N., Giwa, A. (2018b). “Experimental Study of High Liquid Viscosity Oil-Gas Flows using ECT and Gamma Radiation Methods.” Petroleum & Coal 60 (2), 2018

Azamathulla, H. and Ahmad, Z. (2013). Estimation of Critical Velocity for Slurry Transport through Pipeline Using Adaptive Neuro-Fuzzy Interference System and Gene-Expression Programming - Journal of Pipeline Systems Engineering and Practice 2013 4:2, 131-137

Baba Y., Aliyu A., Archibong A., Almabrok A, Igbafe A. (2018). “Study of High Viscous Multiphase Flow in a Horizontal Pipe.” Heat and Mass Transfer 54 (3), 651–669, 2018

Charles, M.E., (1970), Transport of solids by pipelines, 1st International Conference on Hydraulic transport of solids in pipes, 1st- 4th September.

Charles, M.E., Govier, G.W. and Hodgson, G.R. (1961), The horizontal pipeline flow of equal density oil/water mixture, Can. J. Chem. Eng., 39, pp. 27-39.

Condolios, E. and Chapus, E. E. (1963), "Transporting solid materials in pipelines", Chemical Engineering, vol. 70, no. 13

Danielson, T. (2007), "Sand Transport Modeling in Multiphase Pipelines", Offshore Technology Conference

Davies, J. (1987), "Calculation of critical velocities to maintain solids in suspension in horizontal pipes", Chemical engineering science, vol. 42, no. 7, pp. 1667-1670

Durand, R. and Condolios, E. (1952), "Hydraulic Transportation of Coal and Solid Material in Pipes", London Colloquium of the National Coal Board.

Durand, R. (1953), “Basic Relationships of the Transportation of Solids in Pipes Experimental Research”, Proceedings Minnesota International Hydraulics Convention, pp. 89-103.

Fajemidupe, O. T. (2016), Effect of particle size on sand deposition in single-phase and multiphase pipelines. *PhD Thesis,* Cranfield University.

Fajemidupe, O. T. (2019), Aliyu A. M., Baba Y. D., Archibong-Eso, A., Yeung, H. (2019), “Sand minimum transport conditions in gas–solid–liquid three-phase stratified flow in a horizontal pipe at low particle concentrations”, *Chem. Eng. Res. Des.,* vol. 143, pp 114-126. https://doi.org/10.1016/j.cherd.2019.01.014.

Gillies, R. G., Shook, C., Kristoff, B. & Parker, P., (1994), “Sand Transport in Horizontal Wells”, *11th Annual Calgary University Heavy Oils and Oil Sands Technology Symposium,* March 2nd

Gillies, R.G., McKibben, M.J., Shook, C.A. (1997), Pipeline flow of gas, liquid and sand mixtures at low velocities, Journal of Canadian Petroleum Technology, 36 (9), pp. 36-42.

Gillies, R.G., Shook, C.A. (2000), Modelling high concentration settling slurry flows, Canadian Journal of Chemical Engineering, 78 (4), pp. 709-716.

Graf, W. H., (1971), “Hydraulics of Sediment Transport”, McGraw-Hill Book Co., Inc., New York.

Guo, J (2002) *Hunter Rouse and Shields Diagram*. In: Advances in Hydraulics and Water Engineering. World Scientific Publishing Company, pp. 1096–1098. https://doi.org/10.1142/9789812776969_0200.

Hanks, RW. (1980). ASME Paper No. 80-PET-45. ASME Energy sources Technology Conf. New Orleans, LA, Feb. 3 to 7, 1980.

Hughmark, G. A. (1961), “Aqueous Transport of Settling Slurry”, *Industrial and Engrg. Chem*, Vol. 55, pp. 389-390

Ibarra, R., Mohan, R.S., Shoham, O. (2014), “Critical Sand Deposition Velocity in Horizontal Stratified Flow. *SPE Int. Symp. Exhib. Form. Damage Control*, (February), pp. 26–28.

Najmi, K., Hill, A. L., McLaury, B. S., Shirazi, S. A., (2015), “Experimental Study of Low Concentration Sand Transport in Multiphase Air–Water Horizontal Pipelines”. *J. Energy Resour. Technol.*, **137** (3), pp. 032908-1– 9.

Oroskar, A. R. and Turian, R. M. (1980), "The critical velocity in pipeline flow of slurries", AICHE Journal, vol. 26, no. 4, pp. 550-558

Oudeman, P., (1993), “Sand Transport and Deposition in Horizontal Multiphase Trunklines of Subsea Satellite Developments”, *SPE Production & Facilities*, pp.237-241

Parzonka, W., Kenchington, J.M. and Charles, M.E. (2018) ‘Hydrotransport of solids in horizontal pipes: Effects of solids concentration and particle size on the deposit velocity’, *The Canadian Journal of Chemical Engineering*, 59(3) Wiley-Blackwell, pp. 291–296.

Rix, S.J. and Wilkinson, S.J., (1991), “*The Conveying of Sand by Two-phase Flows in Horizontal and Inclined Pipes”,* Research Project Report, University of Cambridge, Cambridge UK.

Roco, M.C. 1977. Experimental investigation of critical velocity in pipelines for hydro-transport. *St. Cerc. Mec. Appl.* 36: 111-112.

Salama, M.M., (2000), “Sand Production Management”, Journal of Energy Resources Technology, Vol. 122, pp. 29-33.

Soepyan, F. B., S. Cremaschi, C. Sarica, H.J. Subramani, G.E. Kouba (2014), Solids transport models comparison and fine-tuning for horizontal, low concentration flow in single-phase carrier fluid, *AIChE J.*, vol. 60, 76–122.

Thomas, A. (1979), "Predicting the deposit velocity for horizontal turbulent pipe flow of slurries", International Journal of Multiphase Flow, vol. 5, no. 2, pp. 113-129

Thomas, D. G. (1962), "Characteristics of Suspension: Part VI Minimum Transport Velocity of Large Particle Size Suspensions in Round Horizontal Pipes", A.I.Ch.E Journal, vol. 8, no. 3, pp. 373-378

Thomas, D.G. (1961), “Transport Characteristics of suspensions Part 11 Minimum Transport Velocity of Flocculated Suspensions in Horizontal Pipes”, *AIChE J.*, Vol. 7, 3, 423-430

Turian, R.M., Hsu, F.L. and Ma, T.W. (1987) ‘Estimation of the critical velocity in pipeline flow of slurries’, *Powder Technology*, 51(1), pp. 35–47.

Vatankhah, A. and Peysokhan, P. (2015). Discussion of “Estimation of Critical Velocity for Slurry Transport through Pipeline Using Adaptive Neuro-Fuzzy Interference System and Gene-Expression Programming” by H. Azamathulla and Z. Ahmad - Journal of Pipeline Systems Engineering and Practice 2015 6:1

Wasp, E J, T. C. Aude, J P Kenny, R. H. Seiter, and R. B. Jacques. 1970. “Deposition Velocities, Transition Velocities and Spatial Distribution of Solids in Slurry Pipelines.” In *1st International British Hydromechanics Research Association Hydraulic Transport of Solids in Pipes Conference*, 53–76. Coventry, UK: BHR Group. https://trid.trb.org/view.aspx?id=19585.

Wasp E. J., J. P. Kenny, R. L. Gandhi, (1977). Solid–Liquid Flow in Slurry Pipeline Transportation. Clausthal, Germany: Trans-Tech.

Wicks, M., (1971), “Transport of Solids at Low Concentrations in Horizontal Pipes”, In Zandi, I (Ed.), Advances in Solid-Liquid Flow in Pipes and its Applications, Pergamon Press, pp.101-124.

Yan, W. (2010) Sand transport in multiphase pipelines, PhD thesis. Cranfield University, UK.

Zhao Y., Yeung H, Zorgani E, Archibong A., Lao L. (2013). High Viscosity Effects on Characteristics of Oil and Gas Two-Phase Flow in Horizontal Pipes. Chemical Engineering Science. 95, 343 – 352, 2013.

Zorgani, E. (2012). An experimental study of sand behaviour in multiphase pipelines. (PhD thesis), Cranfield University, UK.