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# Advances in Solid Transport in Multiphase Fluid Flow

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***Abstract***

***The transport of solids is encountered in many industry particularly in the transport of oil and gas multiphase reservoir fluids through a pipeline. Sand transport in multiphase environment is a challenge because of transient flow pattern changes and associated huge pressure drops. Solids are transported in various forms depending on the mean velocity of flow, such as suspension where velocity is high enough, and rolling or saltation where the flow velocity is relatively low.***
***This paper is a literature review covering various aspects of solid transport in multiphase flow in pipes. A description of commonly observed flow patterns of settling slurries in pipes are presented and discussed. Solid transport models developed in the literatures focused mainly on determining the minimum critical velocity to prevent the formation of a stationary bed in the pipeline.***
***The paper summarized the published works with respect to solid transport in multiphase fluid flow in pipeline both of experimental and numerical investigation.The paper made attempts to identify the current state of knowledge and highlighted areas where new development work is required. It provides some insight into critical issues of solids transport processes and some recommendations for future research related to this subject.***

## 1.0 Introduction

Presence of solid in production fluid system is inevitable. At some point in the life of an oil reservoir, reservoir pressure decreases thus increasing the effective stress on the grains. When this induced stress exceeds formation stress, sand is produced [1]. In multiphase flow, water production may dissolve natural cementing materials, weakening the inter-granular bonds and mobilizes fine sand which causes sand to be forced into the wellbore and transported through the tubing to the well head. The velocity required for effective transport of particles as it enters the transport line must be in the turbulent region for horizontal pipes, and for vertical pipes must be greater than the settling velocity of the particles to prevent deposition [2]. Therefore, the ability of fluid in horizontal motion to be able to suspend solid particles depends on the counterbalance of two actions: gravity, which causes the particles to fall or settle in the fluid, and an upward diffusion of the particles, caused by a concentration gradient of particles, which in turn is created by gravity [3,4]. The particle movement thus depends on the properties of the solids; solids density, particle size and particle shape. However, for large and heavy particles, it may take a strong turbulence in order to suspend the particles in a horizontal pipe. Therefore understanding this mechanism of particle suspension helps comprehend what happens to pipe flows of suspended solids. The three compelling forces can be described as

(i) Gravity force, $F_G$ acting downward

(ii) Lift force, $F_L$ acting upward

(iii) Drag force, $F_D$ acting perpendicular, which appears whenever there is a relative motion between the particle and the fluid.

The derivation of the model forces are well documented in the literatures. Generally, the horizontal pipe velocity is the critical criterion of the required velocity in systems with both horizontal and vertical pipes. For a horizontal pipe it can be postulated that the lifting effect of the turbulent fluid should be able to overcome the gravity effect on the particle. The lifting effect depends on the kinetic energy of the fluid, fluid density and on the projected area of the particle [2].

Typically, multiphase operations are carried out under turbulent conditions of varying intensity. In these processes sometimes a uniform dispersion of particles is achieved due to the interaction between turbulent eddies and the dispersed phase. A better

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understanding of such interaction is fundamental to the effective design, modelling and operation of multiphase systems [5]. From a hydrodynamic viewpoint, the most important and fundamental aspects of solid-liquid multiphase flow are inter-phase interaction (i.e., interaction between the fluid phase and the particulate phase) and intra-phase interaction (i.e., interaction among solid particles making up the particulate phase). Inter-phase interaction between the fluid phase and the particulate phase is manifested mainly in the drag force exerted on the particles by the fluid stream and the transfer of momentum from one phase to another [6].

## 2.0 Solid Transport Patterns

The conveying of solids by a fluid in a pipe can involve a wide range of flow conditions and phase distributions, depending on the density, viscosity, and velocity of the fluid and the density, size, shape, and concentration of the solid particles [7 - 9]. In oil & gas multiphase fluid flow, sand is often co-produced with oil especially oil produced from unconsolidated formations. The produced oil with entrained solids can be transported through pipeline to a processing facility nearby or to onshore location. In a typical hydrocarbon transportation, pipeline follows the undulating topography of the offshore seafloors and onshore surfaces. This complex geometry thus has effect on how the solids are transported in the pipeline flowing with hydrocarbons. The classifications of solid transport patterns are fairly consistent with many authors [4,7,10 - 12] and are grouped as pseudo-homogeneous suspensions, heterogeneous suspensions, heterogeneous suspensions with sliding beds, and stationary beds (see Figures 1 and 2). The demarcation between the ‘‘homogeneous’’ and ‘‘heterogeneous’’ flow regimes depends in a complex manner on the size and density of the solids, the fluid density and viscosity, the velocity of the mixture, and the volume fraction of solids [9].

The sand will settle to form beds along the bottom of the pipe if the fluid velocity is below the minimum transport velocity required for rolling or saltation [4,7,13]. These beds can build up and plug the pipe if the velocity is too low, or it can be swept along the pipe bottom if the velocity is near the minimum transport velocity. See Table 1 for descriptions of various liquid-gas-solid flow patterns.

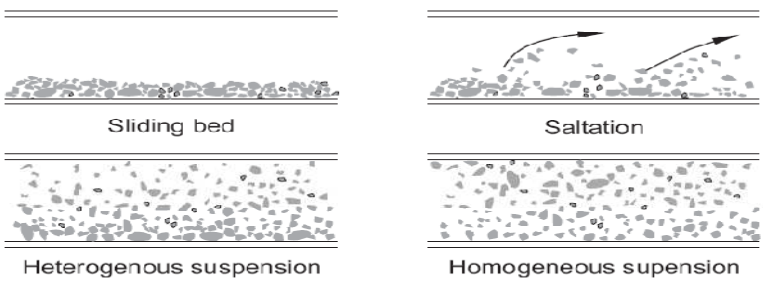


**Figure 1:** Flow Regimes of flow of Settling Slurries in Horizontal Pipe

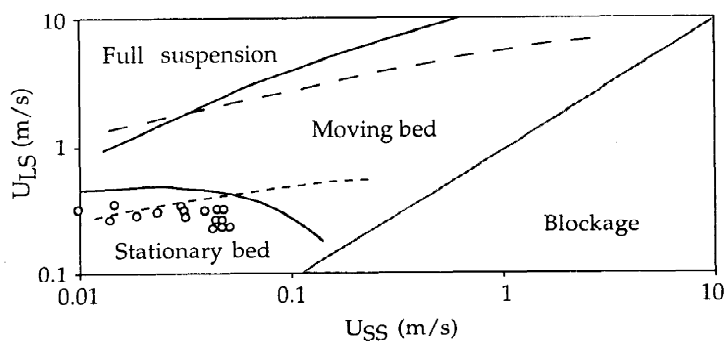


**Figure 2:** A flow pattern map for solid-liquid flow in pipe. Adapted from Barnea

**Table 1:** Solid-fluid Flow Pattern

| **Sand transport modes** | | |
|---|---|---|
| Stationary bed (SB) | Sand is deposited at the bottom of pipes and become stationary. | This occurs at very low liquid or gas velocities. |
| Moving bed (MB) | Loosely packed sand deposited at the bottom of the pipe, first in the form of separated dunes and then as continuous moving bed. The sand grains are either rolling or saltating along the bottom of the pipe. | This will occur at increased velocity which keeps the solids moving along the bottom of the pipe. |
| Suspension flow (SF) | The sand particles are homogeneously suspended within the carrier fluid. This represents ideal dilute phase. | This occurs above the critical velocity. The flow assumes a turbulence condition. |

## 3.0 Solid Transport Models

A number of models for predicting solid transport in multiphase fluids exist in the literatures. This section reviewed some of these works especially as they relates to modelling and experimental explorations. The discussions highlighted methods that are adopted, results obtained and challenges encountered in the various studies. This provided opportunity to highlight the knowledge gap and areas for improvement.

A number of published works in multiphase transport have used particle transport in single phase as basis for the development of their models. The reason for this is the fact that many previous works are related to transportation in coal or bauxite industry [8].

## 4.0 Oroskar and Turian Model

Oroskar and Turian [14] adopted analytical approach for the critical velocity equation and defined a force or energy balance on the particle influenced primarily by the eddy intensity of the turbulent flow and the drag forces. For a case of high particle loading, particles will be subjected to the turbulent core of the fluid and hence will be transported. At low particle loading, similar to what is obtainable in the subsea tieback, the particle will drop to the bottom of the pipe where there is no turbulent eddies and form a stationary bed. Transportation of particle in this case depend on the size of the particle and whether or not is affected by turbulent core. The developed correlation based on turbulent core principle was used for development of critical velocity model as expressed below.

$$V_{OT} = \sqrt{gd(S-1)}\left[1.85C_C^{0.1536}(1-C_C)^{0.3564}\left(\frac{D}{d}\right)^{0.378}\left(\frac{\rho_L D\sqrt{gd(S-1)}}{\mu_L}\right)^{0.09}\chi^{0.3}\right] \quad (1)$$

Where,

$V_{OT}$ = critical velocity, m/s

g = acceleration due to gravity, m/s2

D = pipe diameter, m

d = particle diameter, m

S = ratio of coarse solid density to carrier fluid density

$C_C$ = coarse particle volume fraction (particles exceeding 74 microns)

$\rho_L$ = carrier fluid density, kg/m³

$\mu_L$ = carrier fluid dynamic viscosity, Pa-s

$\chi$ = hindered settling factor

However, there was no mention of solid particle loading, the density and bed thickness. The model is generally extending existing hydraulic conveying models to the multiphase case. This has been found to be inadequate for solid transport in multiphase flow.

## 5.0 Oudeman Model

Oudeman [10] approach was to facilitate the design of sand tolerant systems. This led tocharacterisation of the flow patterns for sand motion as:

(i) Flow with a stationary bed

(ii) Flow with a moving bed and saltation (with or without suspension)

(iii) Heterogeneous mixture with all solids in suspension

Air-water-sand flow experiment was conducted under varying operating conditions. The conclusions drawn are that, the increased sand transport in multiphase flow can be attributed primarily to the increased turbulent associated with the flow. Sand transport increases strongly with gas fraction. Gas increases sand transport much more than increasing liquid velocity. Oudeman therefore described sediment transport in terms of two dimensionless quantities as below

$$\phi = \frac{S}{\sqrt{d^3 g(F-1)}} \quad (2)$$

$$\psi = \frac{v_b^2}{gd(F-1)} \quad (3)$$

Where

$\phi$ = dimensionless sand transport rate

$\psi$ = dimensionless fluid flow rate
S = Transport rate in grain volume per second meter of sand bed width
d = grain diameter
g = acceleration due to gravity
F = Solid – Liquid density ratio
$v_b$ = drag velocity in sand bed

For each gas fraction, a relation between dimensionless transport rate and dimensionless flow rate was expressed in the form of power law as

$$\phi = m\psi^n \qquad (4)$$

Where m and n depend on the input gas fraction.
The effects of different flow patterns, particle density and concentration profiles on particle transport were not considered and these have direct influence on sand transport.

## 6.0 Turian et al Model

Turian et al [15]developed one of the widely used solid transport model that correlated a total of 864 experimental critical velocity data, representing a broad variety of solid materials and pertaining to wide ranges of the variables. This was used as the basis for developing a set of critical velocity correlations, established by fitting the data to various forms of standard equations. The expression is as presented below:

$$\frac{v_c}{\sqrt{gD(s-1)}} = 1.7951C^{0.1087}(1-C)^{0.2501}\left(\frac{d}{D}\right)^{0.0662}\left(\frac{D\rho_L\sqrt{gD(s-1)}}{\mu_L}\right)^{0.0017} \qquad (5)$$

Other researchers [13] adopted an analytical approach. The analytical result indicates that $v_c$ depends on pipe diameter and on particle size which was in agreement with the conclusion drawn by Oroskar and Turian [14] which gave the best empirical fits to the data.

## 7.0 Gillies et al Model

Gillies et al [16] conducted experiments to investigate the ability of gas-liquid mixtures to transport sand in a horizontal pipe or well at low velocities. Both laminar and turbulent liquid flow regimes were investigated. He then extended the Meyer-Peter correlation for hydraulic conveying of slurries to multiphase flow and found that the sand transport rates for sand beds could be roughly predicted. Gillies et al [16] extended Meyer-Peter model by relating dimensionless particle flux to dimensionless shear stress as shown below:

$$\phi = \frac{(q_S/S_S)}{\left[gd^3(S_S-1)\right]^{0.5}} \qquad (6)$$

$$\psi = \frac{\rho_L gd(S_S-1)}{\tau_O} \qquad (7)$$

$$\tau_O = \frac{fV^2\rho_M}{2} \qquad (8)$$

Where,
$S_S$ = Solid – Liquid density ratio
d = Particle diameter
g = Acceleration due to gravity
$q_S$ = Volumetric flow rate of the mixture per unit bed width multiplied by the delivered volume fraction of solids
$\psi$ = Dimensionless shear stress
$\rho_L$ = Liquid density
f = friction factor for flow over a bed with a relative roughness ( $d/D_{eq}$ )
V = mean velocity of the flow above the sand deposit ( $V = Q/A_O$ )
$D_{eq}$ = hydraulic equivalent diameter

Q = flow rate

$A_O$ = contact flow area

$\rho_M$ = mean density of the delivered mixture

Meyer-Peter equation links $\psi$ and $\phi$ by:

$$\phi = \left[\left(\frac{4}{\psi}\right) - 0.188\right]^{1.5} \qquad (9)$$

This can also be rearranged to provide a prediction of the flow rate. Gillies et al concluded that gas injection has limited influence on the ability of a laminar flow to transport sand at low superficial velocities. They observed that gas injection can increase the solid transport rate if the flow is turbulent. This was similar to conclusion reached by Oudeman [10] on gas increase with sand transport.

## 8.0 King et al Model

King et al [17] extended the model of Thomas [18] for hydraulic conveying. The model calculates the minimum pressure gradient for solid transport to occur. It takes into account the viscous sub-layer and particle settling velocity, but the results can only be compared within the viscous sub-layer either with a larger or smaller particle diameter.

For a case where the particle diameter is smaller than the viscous sub-layer thickness, the friction velocity $U_O^*$ at deposition for infinite dilution is given by:

$$U_O^* = \left[100 w_s \left(\frac{\nu}{d}\right)^{2.71}\right]^{0.269} \qquad (10)$$

For a case where the particle diameter is bigger than the viscous sub-layer thickness, the friction velocity $U_O^*$ at deposition for infinite dilution is given by:

$$U_O^* = \left[0.204 w_s \left(\frac{\nu}{d}\right)\left(\frac{\nu}{D}\right)^{-0.6}\left(\frac{\rho_S - \rho_L}{\rho_L}\right)^{-0.23}\right]^{0.714} \qquad (11)$$

For a system with a greater particle concentration, the infinite dilution value can be modified to account for the presence of other particles. This correction is only applied if the particle diameter is in excess of the boundary layer thickness and is given by:

$$U_C^* = U_O^*\left[1 + 2.8\left(\frac{w_s}{U_O^*}\right)^{0.33}\sqrt{\Phi}\right] \qquad (12)$$

Where,

$w_s$ = Particle settling velocity (ft/s) under quiescent conditions

υ = Kinematic viscosity (ft/s)

d = Particle diameter (ft)

D = Pipe diameter (ft)

$\rho_S, \rho_L$ = Solid and liquid densities (lb/ft3)

$\Phi$ = Volume fraction of solids in the slurry

The height of the laminar sub-layer, δ for a smooth pipe and for Reynolds numbers below $10^7$ is given by:

$$\delta = 62D\left(\frac{DU_{SL}\rho_L}{\mu_L}\right)^{-7/8} \qquad (13)$$

Where, $U_{SL}$ is the liquid superficial velocity (ft/s)

The particle velocity under quiescent conditions is dependent on the particle Reynolds number and can be divided into three regimes. The particle Reynolds number is defined as;

$$R_{ep} = 1488\frac{dw_s\rho_L}{\mu_L} \quad (14)$$

For $R_{ep}$ < 2, Stoke's law region

$$w_s = 1488\frac{gd^2(\rho_S - \rho_L)}{18\mu_L} \quad (15)$$

For 2< $R_{ep}$ <500, intermediate region

$$w_s = \frac{3.54g^{0.71}d^{1.14}(\rho_S - \rho_L)^{0.71}}{\rho_L^{0.29}\mu_L^{0.43}} \quad (16)$$

For $R_{ep}$ >500, Newton's law region

$$w_s = 1.74\sqrt{\frac{gd(\rho_S - \rho_L)}{\rho_L}} \quad (17)$$

Based on above relations the pressure gradient for minimum transport to occur can be estimated as:

$$\frac{\Delta p}{\Delta x} = \frac{4\rho_L(U_C^*)^2}{D} \quad (18)$$

If the pressure gradient for minimum transport is lower than the pressure drop predicted by a multiphase flow correlation then the particles would be transported.

The model proffered method for estimating pressure gradient prediction, but they did not treat both minimum velocity required to transport sand particle in pipes.

## 9.0 Stevenson et al Model

Stevenson et al [8] conducted an experiment to study sand transport at low loading in multiphase flow. This is a typical level of concentration in the transport of sand by oil and gas in subsea pipelines / tiebacks. It stressed the influence of turbulent slug nose and its effect on sand mobility. It highlighted fundamental flaws in extending work from hydraulic conveying where there is no resemblance to transportation of solid in multiphase oil and gas flow. The approach was to obtain dimensionless transport velocity correlations based on experimental observations. The correlations are as given below

For low viscosities, < 4.1cP

$$V_P = 0.951V_{SL}\left(1+\frac{V_{SG}}{V_{SL}}\right) - \left(1.36\frac{V_{SG}}{V_{SL}} + 0.852\sqrt{F_{rL}}\right)\left(R_{eL}\sqrt{F_{rL}}\left(\frac{d}{D}\right)^{1.5}\right)^{-0.181} \quad (19)$$

For high viscosities, >4.1cP

$$\left(\frac{V_P}{V_{SL}}\right)\left[R_{eL}\sqrt{F_{rL}}\left(\frac{d}{D}\right)^{1.5}\right]^{-1.10} = 0.0167 + 0.00593\frac{V_{SG}}{V_{SL}} - 0.00914\sqrt{F_{rL}} \quad (20)$$

Where,

$$F_{rL} = \frac{V_{SL}}{\sqrt{gD}} \quad (21)$$

$$R_{eL} = \frac{\rho_L V_{SL} D}{\mu_L} \quad (22)$$

## 10.0 Danielson Model

Danielson [12] used SINTEF database to obtain the following relation for the critical velocity:

$$U_c = K\nu^{-n/(2-n)}d^{n/(2-n)}(gD(s-1))^{1/(2-n)} \quad (23)$$

Where *d* is the sand particle diameter, *D* is the pipe diameter, *g* is the acceleration due to gravity, sis the ratio of sand particle to carrier fluid density, and *K* and *n* are equal to 0.23 and 0.2 respectively.

The correlation was based on turbulence theory by considering the energy dissipated from turbulent eddies. It equates the strength of turbulence eddies to entrained particles into the fluid against gravity forces, which acts to settle the sand particles out. When the condition of the critical velocity is attained, the energy required for the particles to remain in the suspension must be equal to the fraction of turbulent energy effective in suspending them.

The concept of low loading was adopted similar to Stevenson approach. An essential feature of the model is that the critical slip between the liquid and solid phases is unaffected by the presence of gas.

**Key Characteristics of some of the existing solid transport models**

**Table 2:** Comparison of the features of proposed MTV models with selected models

| S/N | Model | Features / Characteristics |
|---|---|---|
| 1 | Stevenson [8] | • Semi-empirical model<br>• Considered two-phase, gas-water<br>• Particle-particle interaction not considered<br>• Considered only intermittent slug flow<br>• Considered only suspension velocity<br>• Small pipe sizes used, max 0.07m<br>• Suitable for horizontal pipe<br>• Sand particle concentration less than 0.1% |
| 2 | Salama [11] | • Semi-empirical model<br>• Considered two-phase flow<br>• Does not account for flow patterns<br>• Particle size distribution not considered<br>• Suitable for horizontal pipe |
| 3 | Danielson [12] | • Drift flux model<br>• Two-phase, water-gas flow<br>• Suitable for horizontal pipe |
| 4 | Thomas [18] | • Mechanistic model using sliding bed concept<br>• Hydraulic conveying<br>• Single-phase, water-sand flow<br>• High solid loading<br>• Suitable for horizontal pipe |
| 5 | Ramadan [20] | • Mechanistic model, three layer concept<br>• Consider two-phase, water & PAC solution<br>• Suitable for horizontal and inclined pipes<br>• Assumed stratified flow pattern<br>• Consider only suspension velocity<br>• Considered particle size distributions |

## 11.0 Conclusion

Sand influx from relatively low strength formation is inevitable. The deep and ultra deep offshore environments are prone to sand influx because of the characteristic highly unconsolidated reservoir at shallow depth occasioned by high pressures and high temperatures. The production of formation sand into the wellbore and topside facilities is a common problem with attendant adverse effect on well productivity and equipment.

From the literatures reviewed, it can be established that many of the current works have been largely focused on single and two phase flow. The review also highlighted the fundamental flaws in extending hydraulic conveying theory to particle transport in multiphase flow. Many of the models [14 - 16, 18, 19] also reflects high sand loading as against typical low sand loading of less than 1 in 1000 by volume, a level of concentration encountered in the transport of sand by oil and gas in subsea pipelines [8,21]. The influence of flow patterns and flow pattern transitions in multiphase fluids are rarely considered [22]. This may have been responsible for lack of accuracy of these models and which results into inappropriate solid transport models for three-phase and four-phase. For accurate development of multiphase solid transport model, Kan et al [1] recommended that the model must be applicable in various flow patterns.

In order to bridge these gaps in knowledge, the models must adopt an integrated multiphase flow management system supported with comprehensive experimental investigation of solid behaviours in multiphase fluid flow. The multi-fluid modelling and simulation methods coupled with experimental investigation could provide the key to unlocking the complexities of solid transport in multiphase fluids in pipeline/tiebacks.

## 12.0 References


[1] KAN, W.C., LIM, P. W., LIM, L.T., ANOSIKE, F., SHOUSHTARI, M.A. and SAAID, I.M. " A Comparative Study on Sand Transport Modeling for Horizontal Multiphase Pipeline". 2014, Research Journal of Applied Sciences, Engineering and Technology 7(6): 1017-1024.

[2] BROOK, N. "Fluid Transport of Coarse Solids". Mining Science and Technology, 1987, Vol. 5, pp. 197-217

[3] GOVIER, G.W. and AZIZ, K. "The Flow of Complex Mixtures in Pipes". 1972, 4th ed. Malabar Florida: Robert E. Krieger Publishing Company.

[4] LIU, H. "Pipeline Engineering". 2003, Lewis Publisher, A CRC Press Company.

[5] DOROODCHI, E., EVANS, G.M., SCHWARZ, M.P., LANE, G.L., SHAH, N. AND NGUYENA, A. "Influence of turbulence intensity on particle drag coefficients". 2008, Chemical Engineering Journal, 135, pp. 129-134.

[6] DOAN, Q. AND GEORGE, A.E. "Flow of Oil and Sand in a Horizontal Well". 1998, Journal of Petroleum Technology, 37(10), pp. 39-45

[7] PEDEN, J.M., FORD, J.T. AND OYENEYIN, M.B. "Comprehensive Experimental Investigation of Drilled Cuttings Transport In Inclined Wells Including the Effects of Rotation and Eccentricity". 1990, The Hague, Netherlands: SPE. pp. 393-404

[8] STEVENSON, P. " The Transport of Particles at Low Loading in Near-Horizontal Pipes by Intermittent Flow". 2001 Chemical Engineering Science, 56, pp. 2149-2159.

[9] DARBY, R., "Chemical Engineering Fluid Mechanics". 2001, Second ed. New York, USA: Marcel Dekker, Inc.

[10] OUDEMAN, P. "Sand Transport and Deposition in Horizontal Multiphase Trunk lines of Subsea Satellite Developments". 1993, SPE Production & Facilities,

[11] SALAMA, M.M. "Sand Production Management". 2000, Journal of Energy Resources, 122, pp. 29-33

[12] DANIELSON, T.J. "Sand Transport Modeling in Multiphase Pipelines". 2007, Offshore Technology Conference. May. Houston, USA: SPE.

[13] BELLO, K.O., OYENEYIN, M.B. AND OLUYEMI, G.F. "Minimum Transport Velocity Models for Suspended Particles in Multiphase Flow Revisited". 2011, SPE Annual Technical Conference & Exhibition, Denver, USA.

[14] OROSKAR, A. R., AND TURIAN, R. M. "The Critical Velocity in Pipeline Flow of Slurries". 1980, Journal of American Institute of Chemical Engineers, 26(4), pp. 550-558

[15] TURIAN, R. M. AND YUAN, T. F. "Flow of slurries in pipelines". 1997, Journal of American Institute of Chemical Engineers, 23, pp. 232-243.

[16] GILLIES, R. G., MCKIBBEN, M. J. AND SHOOK, C. A. "Pipeline flow of gas, liquid and sand mixture at low velocity". 1997, Journal of Canadian Petroleum Technology, , pp. 36-42

[17] KING, M.J.S., FAIRHURST, C.P. AND HILL, T.J. "Solid Transport in Multiphase Flows - Application to High Viscosity Systems". 2001, Transaction of ASME, 123, pp. 200-204.

[18] THOMAS, A.D. "Predicting the Deposit Velocity for Horizontal Turbulent Pipe Flow of Slurries". 1979, International Journal of Multiphase Flow, 5, pp. 113-129.

[19] THOMAS, A.D. "Transport Characteristics of Suspension Part IV". 1962, Journal of American Institute of Chemical Engineers, 8, pp. 373-378.

[20] RAMADAN, A., SKALLE, P. and SAASEN, A. "Application of a Three-Layer Modeling Approach for Solids Transport in Horizontal and Inclined Channels". 2005, Chemical Engineering Science, 60, pp. 2557-2570.

[21] SOEPYAN, F.B., CREMASCHI, S., SARICA, C., SUBRAMANI, H.J. and KOUBA, G.E. "Solids transport models comparison and fine-tuning for horizontal, low concentration flow in single-phase carrier fluid". 2014, Journal of American Institute of Chemical Engineers, Vol. 60, Issue 1, pg 76 - 122.

[22] BELLO, K.O. and IDIGBE, K.I. "Development of a New Drag Coefficient Model for Oil and Gas Multiphase Fluid Systems". 2015, Nigerian Journal of Technology (NIJOTECH), Vol. 34 No. 2, April 2015, pp. 280 – 285.