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Research Article

A Comparative Study on Sand Transport Modeling for Horizontal Multiphase Pipeline

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Abstract: Presence of sand causes adverse effects on hydrocarbon production, pipeline erosion and problems at wellbore. If the problems persist, production may be stopped and delayed. This imposes workover cost. Hence, operating expenses increase and revenue reduces. There is no explicit calculation algorithm for sand transportation modeling readily available in flow simulators. Therefore, this study aims to develop an Excel-based spreadsheet on sand transportation to predict sand critical velocity and onset of sand deposition based on published literature. The authors reviewed nine sand transportation models in pipelines and made comparisons on the selected models based on various criteria. Four of which were then developed into a sand modeling spreadsheet. The four models are the Turian *et al*. (1987), Oudeman (1993), Stevenson *et al*. (2002b) Model and Danielson (2007). The spreadsheet presently focuses on sand production prediction in horizontal two-phase flow. The Danielson model can predict sand hold up while the other models estimate grain size transportable and critical velocity of sand. Flowing pipeline properties, sand properties and results of simulations like using OLGA (for flow rate, velocity and superficial velocity of different phases) are necessary inputs of the spreadsheet. A user selects any model based on different operating conditions or user preference. The spreadsheet was validated by comparing data extracted from the research papers. Sensitivity analyses can also be performed with the spreadsheet by manipulating the parameters such as grain size and flow rate. This review is useful for flow simulators' development to include sand transport modeling.

Keywords: Critical velocity, Danielson model, maximum transportable sand size, Oudeman model, Stevenson model, Turian model

INTRODUCTION

There are several reasons to explain the presence of sand in production systems. Over time, reservoir pressure decreases, thus increasing the effective stress on the grains. Production then induces stress on formation sand. When this induced stress exceeds formation stress, sand is produced. In multiphase flow, water production may dissolve natural cementing materials, weakening the intergranular bonds and mobilizes fine sand which causes sand to be forced into the wellbore. Poorly consolidated reservoirs or low formation strength also leads to sand production. In addition, when gravel pack fails, sand may intrude the well and appear in the pipelines (Danielson, 2007).

The presence of sand in the production system may have adverse effects on the health of production. Sand transport along pipeline is categorized into various methods namely, in decreasing order of velocity, homogenous and heterogeneous suspension and saltation, sliding and eventually settling into a stationary bed load. In homogenous suspension, the flow is of high velocity and turbulent, causing more sand particles to be suspended in fluid. Usually, at this stage, no bed is clearly formed. Higher concentration of sand is apparent nearer to the bed in heterogeneous suspension compared to homogenous suspension. If velocity continues to reduce, saltation or bouncing may occur. Sand sliding or rolling along the pipeline may occur as velocity decreases and concentration near the bed increases. When flow velocity in pipe drops low enough, below the critical velocity, the sand settles down and deposits to form a sand bed (Admiraal, 2003; Oroskar and Turian, 1980).

To avoid the formation of stationary sand bed, the fluid velocity should be higher than a threshold velocity value, termed as critical velocity. Critical velocity can be defined as the minimum velocity demarcating flows that result in sand settlement and incipient sand bed formation at the bottom of the pipe from fully suspended flows. It can also be referred to as the minimum carrying or limiting deposition velocity.

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Below the critical velocity, sand drops out of fluid to form a stationary bed. Increased sand deposition at a point decreases the cross sectional area, eventually increasing the fluid velocity until the critical velocity is reached and sand deposition is seized (Danielson, 2007).

Fluid flow in horizontal pipe can be described in six modes, which are stratified smooth flow, stratified wavy flow, annular mist flow, slug flow, elongated bubble flow (plug flow) and dispersed bubble flow. In vertical pipe, fluid flow in four distinct patterns which are bubble flow, slug flow, churn flow and annular flow (BP Exploration, 1994). As discussed above, sand is deposited when the fluid velocity is lower than the critical velocity. Inclination, gas and liquid rates, flow regime and viscosity and slippage are other factors initially considered in this review.

The objectives of this study are to review and compare some available models in literature for sand transportation in pipeline and present an Excel-based simulation work that estimates sand critical velocity and onset of sand deposition based on the published literature. This review will be useful in the development of flow simulators to include sand transport modeling.

LITERATURE REVIEW

A comparison table of sand transport models was created and it summarizes the objectives of the sand transport modeling studies, inclination and flow regime of experiments of the studies, special conditions, experimental fluids involved in the studies, pressure and temperature of the experiments, results and comments on the studies. The nine models studied are the Oroskar and Turian (1980), Turian *et al.* (1987), Oudeman (1993), Doan *et al.* (1996), Gillies *et al.* (1997), Stevenson (2002a, b), Stevenson *et al.* (2001), Yang *et al.* (2007), Danielson (2007) and Oladele Bello (2008) models. Almost all the models reviewed are used in horizontal or near horizontal applications while the Yang *et al.* (2007) studies straight inclined pipelines. The Bello (2008) studies horizontal, vertical and inclined pipelines.

In the Oroskar and Turian (1980) and Turian *et al.* (1987) model, the authors compared results of their correlations with published correlations. There was no information on the input solid particle loading, particle density and bed thickness for specific measurements given in the Oudeman (1993). This model experimented on air-water-sand over four series of experiments. Doan *et al.* (1996) studied only oil and solid transport inside a horizontal well.

Gillies *et al.* (1997) focused on pressure gradient. While pressure gradient can be used as measures for sand transport and deposition, there are claims that uncertainty in pressure gradient predictions may lead to erroneous results. Furthermore, this model did not include sand transport characteristics and optimal transport velocity. The Meyer-Peter equation used can only estimate delivery sand concentrations in the gas-water-sand flow experiments with 0.01 mm sand and did not give good prediction for gas-free flows. The Stevenson *et al.* model studied horizontal and near-horizontal flow geometries with intermittent and stratified flow patterns. This model could also be useful for further study. However, if solid fraction is much greater than 100 ppm, the isolated particle approach discussed becomes invalid. The difference in results was explained by a shorter length of plug and slug used in the experiment compared to actual plug and slug length in industrial multiphase flow.

Yang *et al.* (2007) used in straight inclined pipelines for stratified gas-liquid two-phase flow was not selected to be further studied as dealing with oil-gas-sand multiphase pipe flows is complex and numerical methods for solving the governing and several constitutive equations are not completely developed. Danielson (2007) could be used for gas-liquid-solid phase flow and showed good fit of data when OLGA2000 is applied. Bello (2008) could also be used for three-phase flow and it is coded by using Microsoft Visual Basic 7.0 software. This model could be used for many different flow regimes: dispersed bubble, stratified, intermittent and annular flow, as compared to the other models which have limited usage depending on the flow regime.

METHODOLOGY

Research papers on published works on sand transport modeling in multiphase flow through pipelines have been reviewed. From the nine models reviewed, four models have been carefully selected to produce a spreadsheet to model sand transport in pipelines in Microsoft Excel. The spreadsheet was developed based on the Turian *et al.* (1987), Oudeman (1993), Stevenson *et al.* (2002b) and Danielson (2007). The necessary inputs of the spreadsheet are particles diameter, particles density, fluid density, fluid viscosity, pipe diameter, particle volume fraction, fluid velocity, fluid superficial velocity and fluid flow rate. The last three variables aforementioned are to be imported from results of base simulations in flow simulators. The spreadsheet focuses on sand transport modeling in two-phase (liquid-sand or gas-sand flow) and horizontal flow. The equations derived by the researchers were reviewed and included in the spreadsheet.

There are six sheets in the spreadsheet. The first sheet contains guidelines on how to use the spreadsheet and the input table; the second sheet provides a unit conversion calculator to ease users to key in input in its required units; and the remaining four sheets are the four sand transport models, respectively. Users are required to provide the necessary inputs of the correct required units in the first sheet of the sand modeling spreadsheet. The inputs will be automatically linked to the respective sand model sheets.

The four models are used to calculate the critical velocity or the minimum superficial velocity required to keep the particles entrained. It can be used to get the liquid flow rate required to keep particles entrained by multiplying with the flowing area (Option 1). In addition, the equations of the Turian *et al.* (1987), Oudeman (1993) and Danielson (2007) are rearranged to back-calculate the maximum particle size transportable by taking the assumption that the input liquid flow rate, subsequently the superficial liquid velocity becomes the critical velocity. This is to indicate the maximum particle size transportable for the particular flow rate, above which the larger particles may deposit (Option 2). Furthermore, the Danielson (2007) can be used to estimate the sand hold up based on calculated critical velocity (Option 3).

Two sensitivity studies using Options 1 and 2 have been designed to examine the minimum flow rate required to transport particle and the maximum size of particle which can be transported in the pipeline, with the critical velocity calculated. In the first sensitivity study, particle size is maintained while varying flow rates. Users can fill in ten different liquid flow rates and one grain size of interest for this sensitivity study. Varying the flow rate will result in different superficial liquid velocity. In the second sensitivity study, liquid flow rate is maintained for all particle size but a range of grain size is used. Users can fill in ten different grain sizes and one liquid flow rate of interest in this sensitivity study. Varying the particle size will result in different critical velocity. In both studies, when the liquid flow rate (superficial liquid velocity) is above the critical velocity, the sand is being entrained. When the liquid flow rate (superficial liquid velocity) is below the critical velocity, sand will be deposited. By observing the plot (plot of critical velocity against liquid flow rate for Option 1 and plot of critical velocity against grain size for Option 2), the minimum flow rate to transport the particle and the maximum grain size which is transportable by the input liquid flow rate can be identified, that is, the point of intersection of the two plots.

In Turian *et al.* (1987), sand transport is treated as non-colloidal slurry flow and a velocity that is lower than the critical velocity results in formation of solid bed at the bottom of the pipe. Pipe walls are smooth. Particles are deposited from fully suspended flow and assumed to be uniformly-sized spherical particles. Both options of calculations are available in the Turian *et al.* (1987), that is, to calculate the critical velocity using Eq. (1) and to calculate the maximum particle size transportable by taking the assumption that the input liquid flow rate becomes the critical velocity with Eq. (2):

$$V_c = 1.7951 * C^{0.1087} * (1 - C)^{0.2501} * \left[\frac{D\rho_l\sqrt{gD(s-1)}}{\mu_d}\right]^{0.00179} * \left(\frac{d}{D}\right)^{0.06623} * \sqrt{2gD(s-1)} \quad (1)$$

$$d = D * V_c^{1/0.06623} / \left\{ 1.7951 * C^{0.1087} * \right.$$

1−C0.2501∗DρlgDs−1μd0.00179∗2gDs−11 0.06623 (2)

Oudeman (1993) conducted studies on horizontal lines, gas-liquid (water) experimental fluids and stratified wavy to slug flow. The entrainment rate of the sand particles from stationary bed to moving bed and moving bed to suspension mode was found to be dependent on the superficial liquid velocity and a weak function of the superficial gas velocity. The two options aforementioned can be used in the Oudeman (1993), that is, to calculate the critical velocity or the minimum superficial velocity required to keep the particles entrained Eq. (3) and (4) and to calculate the maximum particle size transportable by taking the assumption that the input liquid flow rate becomes the critical velocity Eq. (5) and (6). The coefficient 0.25 in V_b equation is the dimensionless flow rate obtained from study. Note for gas rate of 150 MMscfd is used in experiment conducted:

$$V_b = \sqrt{0.25gd(s-1)} \quad (3)$$

$$Vc = \left(\frac{V_b}{0.15(\frac{\mu_l}{\rho_l D})^{1/8}}\right)^{8/7} \quad (4)$$

$$V_b = 0.15{V_c}^{\frac{7}{8}}(\frac{\mu_d}{\rho_l D})^{1/8} \quad (5)$$

$$d = \frac{{V_b}^2}{0.25g(s-1)} \quad (6)$$

Stevenson *et al.* (2002b) model is applicable to horizontal flow geometries, hydraulic and pneumatic particle convey and intermittent to stratified, moderate turbulent flow. Low particle loading (less than 1% by volume) is assumed. Particle diameter is taken to be smaller than viscous sub-layer thickness. Sand particles are treated as hemispheres which drag instead of roll in their incipient motion. This model calculates critical velocity which indicates the incipient motion of sand particles (Option 1). There are three equations to calculate critical velocity, depending on Reynolds number of hemisphere, Re_h. Equation (7) to (11) is used to obtain Reynolds number of hemisphere, Re_h. The f is an experimentally determined dimensionless coefficient of limiting friction and it is taken as 0.55 when experimental value is not available. There are three equations to calculate critical velocity Eq. (12) to (14), depending on Re_h:

$$\mathrm{Re} = \frac{\rho_f v D}{\mu_d} \tag{7}$$

$$C_f = (100\mathrm{Re})^{-0.25} \tag{8}$$

for 4000<Re<10000:

$$\tau_w = 0.5 C_f \rho_f v^2 \tag{9}$$

$$Q = \frac{\tau_w}{\mu_d} \tag{10}$$

$$\mathrm{Re}_h = \frac{\rho_f Q R^2}{\mu_d} \tag{11}$$

Condition 1: $Re_h \leq 0.5$:

$$V_c = \frac{2.19\left[fRg\left(\frac{\rho_s}{\rho_f}-1\right)\right]^{0.57} D^{0.14}}{\frac{\mu_d}{\rho_f}^{0.14}} \tag{12}$$

Condition 2: $0.5 < Re_h < 500$:

$$V_c = 3.29\left[fg\left(\frac{\rho_s}{\rho_f}-1\right)\right]^{0.41} R^{0.08} D^{0.14}\left(\frac{\mu_d}{\rho_f}\right)^{0.18} \tag{13}$$

Condition 3: $Re_h > 500$:

$$\mathbf{V_c = 11.67\left[fg\left(\frac{\rho_s}{\rho_f}-1\right)\right]^{0.29} R^{-0.29} D^{0.14}\left(\frac{\mu_d}{\rho_f}\right)^{0.43}} \tag{14}$$

Danielson (2007) model is developed for horizontal lines and stratified flow for liquid-gas phase modeling. Only Danielson's liquid-sand model has been made available in this spreadsheet. This model is used to calculate the critical velocity for suspension (Option 1), maximum particle size transportable (Option 2) and then the calculated value can be used to estimate the sand hold up (Option 3). Water is the liquid used in the experiment conducted. The critical velocity is calculated using Eq. (15) with experimentally determined constant of K that is equals to approximately 0.23 based on the SINTEF data. The equation is rearranged to get Eq. (16) to calculate maximum transportable particle size. Sand hold up calculation is to be performed in a table. Users are required to input 20 superficial velocities of interested. The superficial velocities will then be used together with the critical velocity calculated from Option 1 to obtain sand hold up with Eq. (17). The sand trails the carrier liquid by a well-defined critical velocity. When the carrier fluid velocity falls below the critical velocity, sand bed begins to form. The bed height increases until the cross sectional area available to fluid flow is reduced enough to restore the fluid velocity over the bed back to the critical velocity:

$$\boldsymbol{V_c = K(\mu_k)^{-\frac{1}{9}} d^{\frac{1}{9}} (gD(s-1))^{5/9}} \tag{15}$$

$$\boldsymbol{d = \left[\frac{V_c}{K\mu_k{}^{-1/9}[gD(s-1)]^{5/9}}\right]^9} \tag{16}$$

$$\boldsymbol{H_s = \frac{-(V_{SL}+V_{SS}-V_c) \pm \sqrt{(V_{SL}+V_{SS}-V_c)^2 - 4(V_c)(-V_{SS})}}{2(V_c)}} \tag{17}$$

The spreadsheet was validated against the results in the research papers based on the same data used in the research papers.

RESULTS AND DISCUSSION

Table 1 shows the input data employed in this review. The four models give different results on critical velocities and maximum grain size transportable (Table 2). It is found that the Oudeman and Danielson models show similar results. The differences of result are because of the unique conditions applied for in the models. Hence, it is important for users to carefully select which model to use based on the different

Table 1: Input data

Parameter	Value		
Particle density	1442 kg/m^3	89.98 lb/ft^3	
Liquid density	845.5 kg/m^3	52.76 lb/ft^3	
Liquid viscosity	0.15 cp	0.00015 kg/ms	0.00015 lb/ft-s
Pipe diameter	8 inches	0.203 m	
Superficial liquid velocity	1.8 m/s		
Particle diameter	200 micron	0.2 mm	
Gravity acceleration	9.81 m/s		
Flow rate	10000 bbl/d		
Mean fluid velocity	0.008 m/s		
Particle volume concentration	1.5e-16		

Table 2: Results of different models

Model	Critical velocity (m/s)	Critical velocity (bbl/d)	Max. grain size transportable (micron)	Sand hold up
Turian *et al.* (1987)	0.037	654.240	1.537E+20	
Oudeman (1993)	0.638	11243.493	162.912	
Stevenson *et al.* (2002b)	0.174	3053.312		
Danielson (2007)	0.607	10668.723	111.766	0.005

Max.: maximum

Table 3: Sensitivity study of flow rate for Danielson model

Liquid flow rate (bbl/d)	Grain size (micron)	Superficial liquid velocity (ft/s)	Superficial liquid velocity (m/s)	Critical velocity, Vc (ft/s)	Critical velocity, Vc (m/s)	Particle deposition
6000	200	1.119	0.341	1.990	0.607	Yes
8000	200	1.492	0.455	1.990	0.607	Yes
10000	200	1.865	0.569	1.990	0.607	Yes
12000	200	2.239	0.682	1.990	0.607	No
14000	200	2.612	0.796	1.990	0.607	No
16000	200	2.985	0.910	1.990	0.607	No
18000	200	3.358	1.023	1.990	0.607	No
20000	200	3.731	1.137	1.990	0.607	No
22000	200	4.104	1.251	1.990	0.607	No
24000	200	4.477	1.365	1.990	0.607	No

Table 4: Sensitivity study of grain size for Danielson model

Grain size (micron)	Liquid flow rate (bbl/d)	Superficial liquid velocity (ft/s)	Superficial liquid velocity (m/s)	Critical velocity, Vc (ft/s)	Critical velocity, Vc (m/s)	Particle deposition
500.00	10000	1.865	0.569	2.203	0.672	Yes
300.00	10000	1.865	0.569	2.082	0.635	Yes
200.00	10000	1.865	0.569	1.990	0.607	Yes
150.00	10000	1.865	0.569	1.927	0.587	Yes
100.00	10000	1.865	0.569	1.843	0.562	No
80.00	10000	1.865	0.569	1.797	0.548	No
60.00	10000	1.865	0.569	1.741	0.531	No
40.00	10000	1.865	0.569	1.664	0.507	No
20.00	10000	1.865	0.569	1.541	0.470	No
10.00	10000	1.865	0.569	1.427	0.435	No

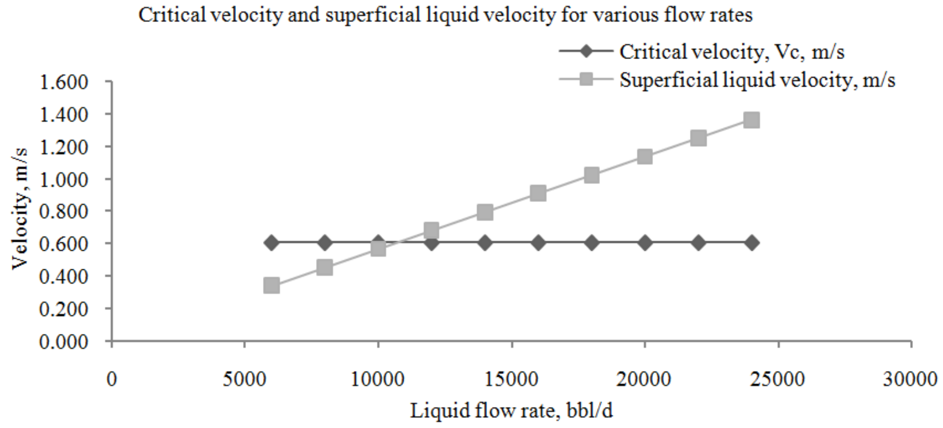


Fig. 1: Graph of sensitivity study of flow rate for Danielson model

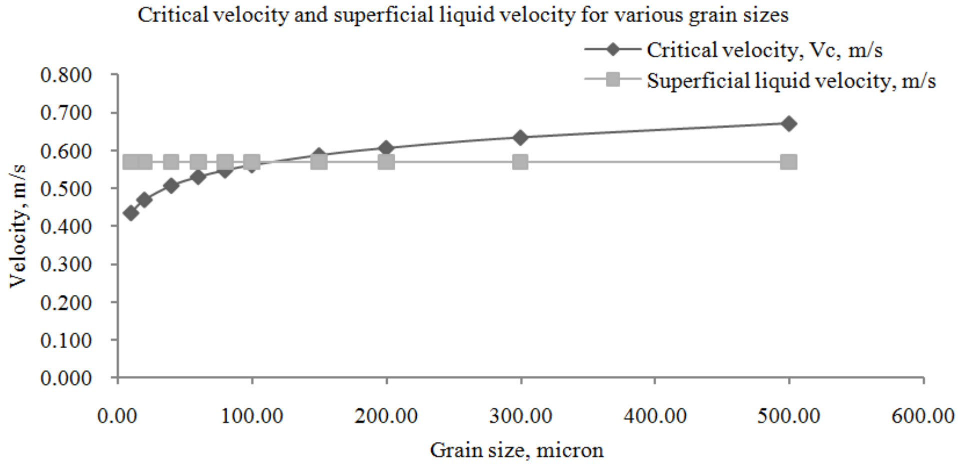


Fig. 2: Graph of sensitivity study of grain size for Danielson model

conditions, that is, the assumptions of the models stated by the authors.

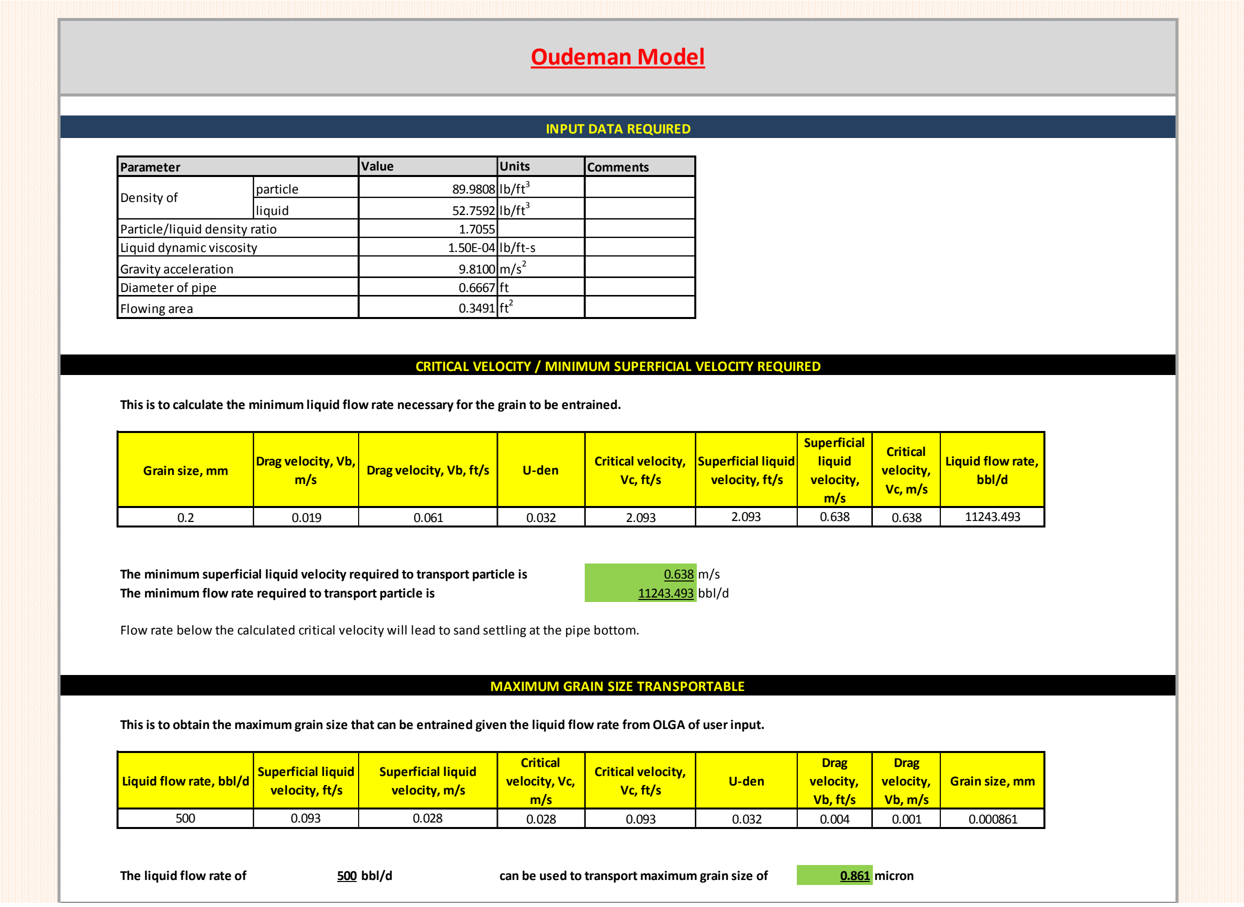
The Danielson model is used to demonstrate the results of sensitivity study in this review. In the first sensitivity study (flow rate), ten different liquid flow rates (6000 to 24000 bbl/d with increment of 2000 each) and grain size of 200 micron are filled in the sensitivity study table (Table 3). The critical velocity, found to be 0.607 m/s for grain size of 200 micron, is compared against the superficial liquid velocities. The intersection point becomes the cutoff point where sand is transportable. From Fig. 1, it can be said that liquid flow rate below 11000 bbl/d will result in potential sand deposition.

In the second sensitivity study (grain size, ten different grain sizes (from 10 micron to 500 micron) and flow rate of interest (10000 bbl/d) are inserted into the sensitivity study table (Table 4). Increasing the grain size increases the critical velocity. The superficial velocity, of 0.569 m/s, is compared against the critical velocity. Likewise, the intersection point becomes the cutoff point where sand is transportable. From Fig. 2, it can be seen that the maximum grand size transportable is 100 micron. Larger grain size than 100 micron will result in potential sand deposition, as shown in Appendix 1 and 2.

CONCLUSION

Sand transport modeling studies performed by researchers were reviewed. Four models were selected to develop a spreadsheet to model sand transport. The four models are Turian *et al*. (1987), Oudeman (1993), Stevenson *et al*. (2002b) and Danielson (2007). The current spreadsheet focuses on two-phase (gas-sand or liquid-sand) horizontal flow and the equations employed by the authors in their studies are developed in the spreadsheet. Properties of sand (size and density), flowing area and results computed from flow simulators may be used as input data for the spreadsheet. The same input data used in the research papers were used to validate the spreadsheet and the results of calculations from the spreadsheet are the same as that in the research papers. A demonstration of results shows the importance of identifying the correct conditions of use to obtain result such as critical velocity, maximum grand size transportable and sand hold up. This further includes a sensitivity study on various flow rates and grain sizes. This review is useful for the continuity of sand transport modeling study and future developments. It is recommended to develop multiphase sand transport model that can be applied in various flow regimes.

Appendix 1:



Oudeman Model

INPUT DATA REQUIRED

Parameter		Value	Units	Comments
Density of	particle	89.9808	lb/ft^3	
	liquid	52.7592	lb/ft^3	
Particle/liquid density ratio		1.7055		
Liquid dynamic viscosity		1.50E-04	lb/ft-s	
Gravity acceleration		9.8100	m/s^2	
Diameter of pipe		0.6667	ft	
Flowing area		0.3491	ft^2	

CRITICAL VELOCITY / MINIMUM SUPERFICIAL VELOCITY REQUIRED

This is to calculate the minimum liquid flow rate necessary for the grain to be entrained.

Grain size, mm	Drag velocity, Vb, m/s	Drag velocity, Vb, ft/s	U-den	Critical velocity, Vc, ft/s	Superficial liquid velocity, ft/s	Superficial liquid velocity, m/s	Critical velocity, Vc, m/s	Liquid flow rate, bbl/d
0.2	0.019	0.061	0.032	2.093	2.093	0.638	0.638	11243.493

The minimum superficial liquid velocity required to transport particle is 0.638 m/s
The minimum flow rate required to transport particle is 11243.493 bbl/d

Flow rate below the calculated critical velocity will lead to sand settling at the pipe bottom.

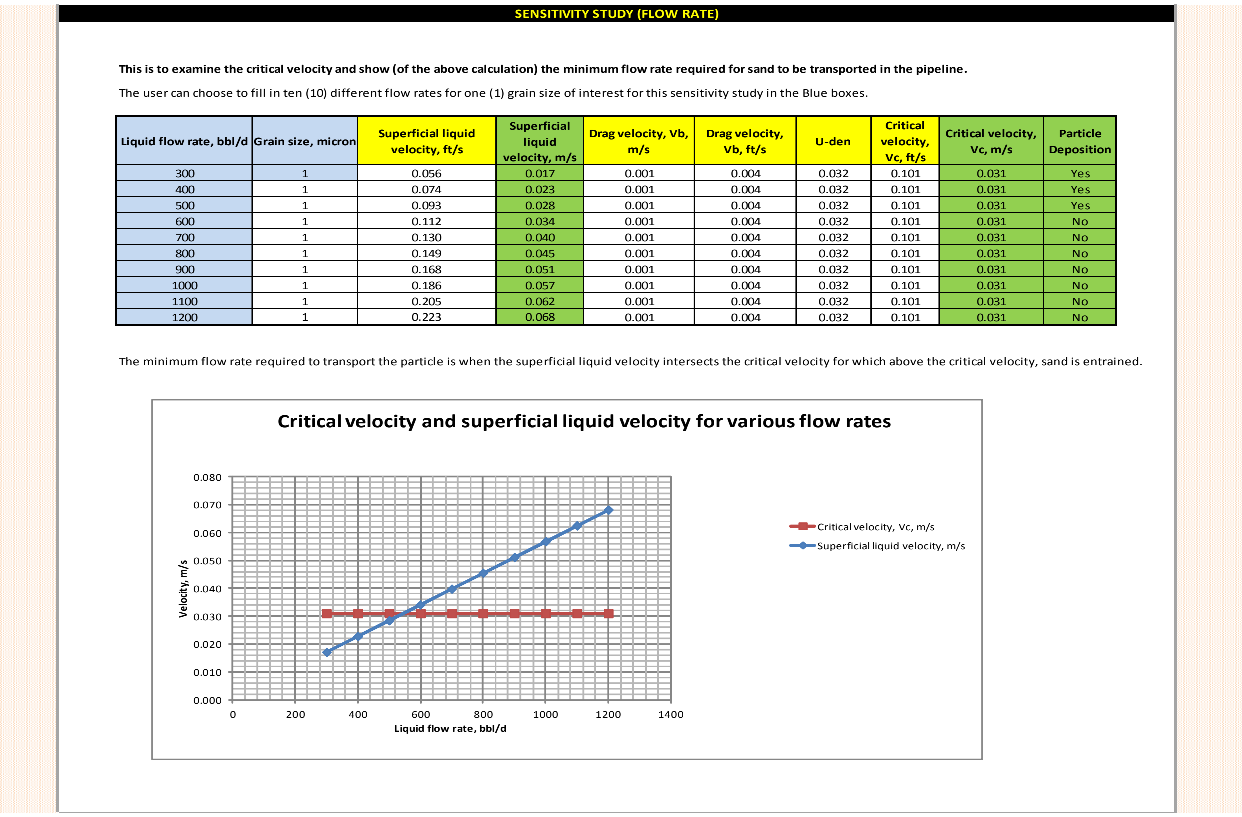
MAXIMUM GRAIN SIZE TRANSPORTABLE

This is to obtain the maximum grain size that can be entrained given the liquid flow rate from OLGA of user input.

Liquid flow rate, bbl/d	Superficial liquid velocity, ft/s	Superficial liquid velocity, m/s	Critical velocity, Vc, m/s	Critical velocity, Vc, ft/s	U-den	Drag velocity, Vb, ft/s	Drag velocity, Vb, m/s	Grain size, mm
500	0.093	0.028	0.028	0.093	0.032	0.004	0.001	0.000861

The liquid flow rate of 500 bbl/d can be used to transport maximum grain size of 0.861 micron

Appendix 2:



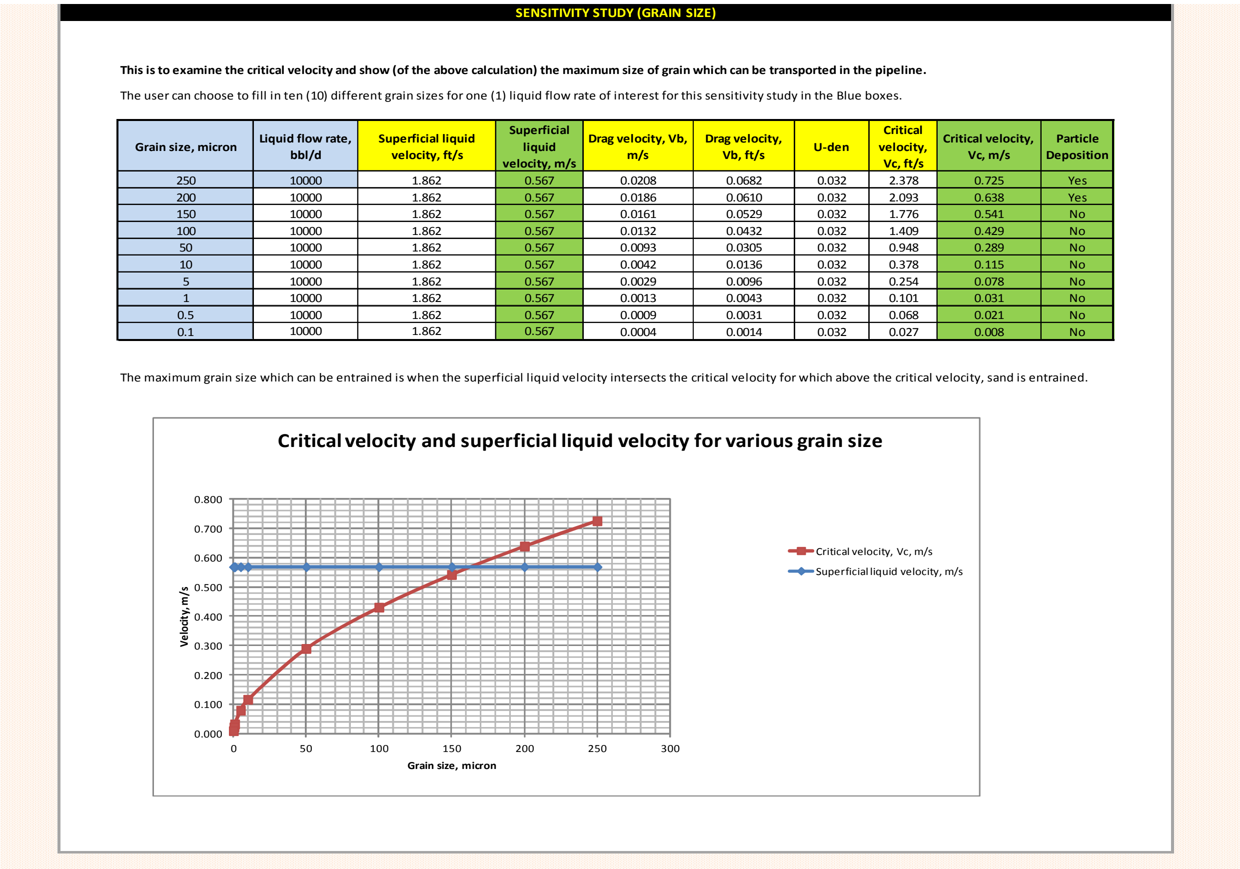
SENSITIVITY STUDY (FLOW RATE)

This is to examine the critical velocity and show (of the above calculation) the minimum flow rate required for sand to be transported in the pipeline.

The user can choose to fill in ten (10) different flow rates for one (1) grain size of interest for this sensitivity study in the Blue boxes.

Liquid flow rate, bbl/d	Grain size, micron	Superficial liquid velocity, ft/s	Superficial liquid velocity, m/s	Drag velocity, Vb, m/s	Drag velocity, Vb, ft/s	U-den	Critical velocity, Vc, ft/s	Critical velocity, Vc, m/s	Particle Deposition
300	1	0.056	0.017	0.001	0.004	0.032	0.101	0.031	Yes
400	1	0.074	0.023	0.001	0.004	0.032	0.101	0.031	Yes
500	1	0.093	0.028	0.001	0.004	0.032	0.101	0.031	Yes
600	1	0.112	0.034	0.001	0.004	0.032	0.101	0.031	No
700	1	0.130	0.040	0.001	0.004	0.032	0.101	0.031	No
800	1	0.149	0.045	0.001	0.004	0.032	0.101	0.031	No
900	1	0.168	0.051	0.001	0.004	0.032	0.101	0.031	No
1000	1	0.186	0.057	0.001	0.004	0.032	0.101	0.031	No
1100	1	0.205	0.062	0.001	0.004	0.032	0.101	0.031	No
1200	1	0.223	0.068	0.001	0.004	0.032	0.101	0.031	No

The minimum flow rate required to transport the particle is when the superficial liquid velocity intersects the critical velocity for which above the critical velocity, sand is entrained.



SENSITIVITY STUDY (GRAIN SIZE)

This is to examine the critical velocity and show (of the above calculation) the maximum size of grain which can be transported in the pipeline.

The user can choose to fill in ten (10) different grain sizes for one (1) liquid flow rate of interest for this sensitivity study in the Blue boxes.

Grain size, micron	Liquid flow rate, bbl/d	Superficial liquid velocity, ft/s	Superficial liquid velocity, m/s	Drag velocity, Vb, m/s	Drag velocity, Vb, ft/s	U-den	Critical velocity, Vc, ft/s	Critical velocity, Vc, m/s	Particle Deposition
250	10000	1.862	0.567	0.0208	0.0682	0.032	2.378	0.725	Yes
200	10000	1.862	0.567	0.0186	0.0610	0.032	2.093	0.638	Yes
150	10000	1.862	0.567	0.0161	0.0529	0.032	1.776	0.541	No
100	10000	1.862	0.567	0.0132	0.0432	0.032	1.409	0.429	No
50	10000	1.862	0.567	0.0093	0.0305	0.032	0.948	0.289	No
10	10000	1.862	0.567	0.0042	0.0136	0.032	0.378	0.115	No
5	10000	1.862	0.567	0.0029	0.0096	0.032	0.254	0.078	No
1	10000	1.862	0.567	0.0013	0.0043	0.032	0.101	0.031	No
0.5	10000	1.862	0.567	0.0009	0.0031	0.032	0.068	0.021	No
0.1	10000	1.862	0.567	0.0004	0.0014	0.032	0.027	0.008	No

The maximum grain size which can be entrained is when the superficial liquid velocity intersects the critical velocity for which above the critical velocity, sand is entrained.

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NOMENCLATURE

bbl/d : Barrel per day
C : Particle volume fraction
C_f : Wall friction coefficient
d : Particle diameter
D : Pipe diameter
f : Dimensionless coefficient of limiting friction
ft/s : Feet per second
g : Gravity acceleration
H_s : Sand hold up
K : Experimentally-determined constant in Danielson Model
m/s : Meter per second
Q : Shear rate
R : Radius of sand hemisphere (0.5 of particle diameter)
Re : Reynolds number
Re_h : Reynolds number of hemisphere
s : Particle to liquid density ratio
v : Mean fluid velocity in the pipe
V_b : Drag velocity at sand bed
V_c : Critical velocity
V_R : Reference velocity
V_{SL} : Superficial liquid velocity
V_{SS} : Superficial sand velocity
μ_d : Liquid dynamic viscosity
μ_k : Liquid kinematic viscosity
ρ_f : Fluid density
ρ_l : Liquid density
τ_w : Shear stress at the pipe wall

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