Proceedings of 18th International Conference on Multiphase Technology, 7-9 June 2017, Cannes, France,
Paper number 15, pp. 363-379

BHR Group
EXPERTS IN FLUID ENGINEERING

Minimum sand transportation conditions in multiphase pipelines: an assessment exercise

Zhang Zhou and Liyun Lao
Oil and Gas Engineering Centre, Cranfield University, Bedfordshire, MK43 0AL, United Kingdom

NOMENCLATURES

d	particle diameter	m
f	fanning friction factor	-
g	gravitational acceleration	$m{\cdot}s^{-2}$
q_s	volumetric flow rate per bed width	$m^3{\cdot}s^{-1}$
m, n	constants	-
s	particle density/liquid density	-
u_o^*	friction velocity at MTC for infinite dilution	$m{\cdot}s^{-1}$
u_c^*	friction velocity at minimum transport condition	$m{\cdot}s^{-1}$
u_t	terminal settling velocity	$m{\cdot}s^{-1}$
C_v	sand volume fraction, v/v	-
D	pipe diameter	m
F_L	Durand coefficient	-
F_r	Froude number	-
GVF	gas void fraction	-
K	coefficients	$m{\cdot}s^{-1}$
MTC	minimum transport condition	-
V_m	mixture flow velocity	$m{\cdot}s^{-1}$
V_c	critical transport velocity	$m{\cdot}s^{-1}$
V_s	particle slip velocity	$m{\cdot}s^{-1}$
V_L	single phase liquid velocity	$m{\cdot}s^{-1}$
V_{SL}	superficial liquid velocity	$m{\cdot}s^{-1}$
V_{SG}	superficial gas velocity	$m{\cdot}s^{-1}$
δ	laminar sublayer thickness	m
μ_l	liquid viscosity	$Pa{\cdot}s$
ν	kinematic viscosity	$m^2{\cdot}s^{-1}$
ρ_g	gas density	$kg{\cdot}m^{-3}$
ρ_l	liquid density	$kg{\cdot}m^{-3}$
ρ_p	particle density	$kg{\cdot}m^{-3}$
φ_s	dimensionless sand transport rate	-
Ω	function of C_V	-
Ψ	Wicks' dimensionless group	-
Ψ_L	dimensionless liquid flowrate	-

1 INTRODUCTION

Sand accumulation in a pipeline could result in blockage and mechanical damage. Although pigging can remove accumulated sand, it can only be used when small amounts of sand are deposited. Another method is to use downhole sand exclusion systems. However, the difficulty of retrofitting these after the reservoir is producing, along with the disruption to operations, cannot be ignored. Sand production management is a method to keep relatively high production rates and maintain system integrity. An essential sand management aspect is to operate the production fluid transport system to satisfy the sand minimum transportation condition (MTC).

A number of definitions for MTC are encountered in the literature due to the different mechanisms that exist for solids transport. Also, various velocity names are used to refer to the similar solids transport conditions by different authors, such as Minimum Transport Velocity, and Solid Transport Velocity, etc. (Yan (2010)). Oroskar and Turian (1980) used the term "critical velocity" as the velocity that marks the transition from the settling of solid particles at the bottom of the pipe to the full suspension of the particles in the flowing fluid. Durand (1952) proposed to use pressure gradient against liquid velocity to identify the critical velocity, which is the velocity corresponding to the minimum pressure gradient level. Thomas (1962)'s definition of MTC was the mean stream velocity required to prevent the accumulation of a layer of sliding particles at the bottom of a horizontal pipe. It is this last definition that is used in this discussion.

Sand transportation in multiphase flow is a very complex issue and dependent on parameters such as sand concentration, fluid viscosities, multiphase (gas-liquid) flow regime and sand particle size. Sand transportation in water flow has been thoroughly studied over 100 years with reference to slurry and hydraulic conveyance. However, the sand concentration involved in slurry studies (Cv > 1% v/v) is usually much higher than that experienced in oil pipelines (e.g. Cv $\approx$50 ppm v/v, or ~50 lb sand per 1,000 bbl of production liquid). In addition, the studies on sand transportation in viscous fluids, i.e. oil, were limited due to the fact that most of the work on hydraulic conveyance used water as medium. However, the understanding of the sand transport mechanism and MTC under those conditions is vital for oil pipeline design to ensure sand transportation at low velocities.

The work reported in this paper focused on an assessment on MTC models developed for liquid/sand flows and gas/liquid/sand flows. A literature review was conducted on published prediction methods with regard to sand transportation. A selective set of these models were benchmarked against the published experimental data and evaluation of model performances has been reported. The exercise started with the models of MTC in single phase liquid flows, followed by the models in gas/liquid flows. An Excel-based prediction tool was developed aiming to provide a straight-forward method to obtain a "sand deposit-free" operating envelope for a multiphase flow pipeline during initial screening.

2 BRIEF REVIEW ON MULTIPHASE FLOW MTC MODELS

2.1 MTC Models in Liquid/Sand Flows

A typical liquid/sand flow is a slurry flow. Hydraulic slurry transport has been experimentally investigated for over a century by many researchers, beginning with the work of Blatch (1906) followed by many extensive research activities. Representative studies for high solid concentration (above 1% v/v) slurry transportation systems include

Durand and Condolios (1953), Durand (1953), Thomas (1962), Wicks (1971), Oroskar and Turian (1980) etc. As mentioned above, typical sand loading or sand volumetric concentration in offshore or subsea applications are much smaller than most industrial slurry transport applications (Yan (2010)). There have only been a few experimental studies focused on solid/liquid transportation at relatively low solid concentration levels to date, including Thomas (1962), Robinson and Graf (1972), Al-lababidi et al. (2012) and Yan(2010).

MTC modelling for liquid/sand flows was therefore initiated for slurry flows. Durand and Condolios (1953) developed a MTC prediction correlation based on their tests on the critical velocity with the particle diameters ranging from 0.2 mm to 25 mm. Solid concentration ranged from 2% to 23% and the pipe diameter ranged from 37.5 mm to 700 mm. The proposed correlation to predict V_c was based on the Froude number of the pipe as follows:

$$V_C = F_L\sqrt{2gD(s-1)} \tag{1}$$

where F_L is the Durand factor based on the particle size and volumetric concentration.

Thomas (1962)'s MTC correlation considered two aspects when analysing the vertical distribution of particles in suspended flow. The first was the ratio between terminal settling velocity and the friction velocity (u_t/u_0^*); the second was the thickness of the laminar sublayer and buffer layer as well as the turbulent core. This (u_t/u_0^*) denotes the particle settling tendency relative to the turbulence driving force to keep particles suspended. Thomas also proposed the lower model and the upper model with the criteria of whether the particle size is bigger than the thickness of the sublayer. His correlation for the friction velocity u_o^* , the friction velocity at minimum transport conditions for infinite dilution, were presented as follows:

$$u_o^* = \left[100u_t\left(\frac{\nu}{d}\right)^{2.71}\right]^{0.269} ,d < \delta$$

and

$$u_o^* = \left[0.204u_t\left(\frac{\nu}{d}\right)\left(\frac{\nu}{D}\right)^{-0.6}(s-1)^{-0.23}\right]^{0.714} ,d > \delta$$

Thomas then developed the correlation between u_c^*, the friction velocity at the MTC, and u_o^*. The correlation, based on experimental data of his 1-inch facilities and other data, was:

$$u_c^* = u_0^*\left[1 + 2.8\left(\frac{u_t}{u_0^*}\right)^{0.33}\sqrt{C_v}\right] \tag{2}$$

The actual MTC velocity is obtained by using:

$$V_C = u_c^*/(f/2)^{0.5} \tag{3}$$

where f is the Fanning friction factor. Note that the velocities used in the Thomas MTC model are in foot/second.

The MTC correlation proposed by Turian et al (1987) was also mainly focused on slurry flow and takes similar form to Equation (1). Particles are treated as non-colloidal. Flow velocity lower than the critical velocity would result in sand bed formation. Sand is considered to deposit under the condition of fully suspended flow and particles are assumed to be regularly shaped with uniform size. The correlation is as follows:

$$V_C = 1.7951 {C_v}^{0.109} (1 - C_v)^{0.25} \left[\frac{D\rho_l \sqrt{gD(s-1)}}{\mu}\right]^{0.0018} \left(\frac{d}{D}\right)^{0.06623} \sqrt{2gD(s-1)} \tag{4}$$

Based on turbulence theory, Davies (1987) developed his MTC prediction correlation. Davies calculated the sedimentation force and the eddy fluctuation force and assumed that, below the MTC, the two forces are balanced. MTC velocity is calculated using:

$$V_c = 1.08(1 + 3.64C_v)^{1.09}(1 - C_v)^{0.55n} \nu^{-0.09} d^{0.18} [2g(s-1)]^{0.54} D^{0.46} \tag{5}$$

where n is the correction index due to the sand concentration.

Salama (2000)'s predictions of MTC also uses the approach based on the theory of turbulence. Some of its parameters were determined according to experimental data, and the final correlation was given as:

$$V_c = \left(\frac{V_{sL}}{V_m}\right)^{0.53} d^{0.17} \nu^{0.09} (s-1)^{0.55} D^{0.47} \tag{6}$$

where V_{sL}/V_m is the ratio between liquid superficial velocity and mixture velocity of multiphase flows. The equation covers the cases of both the liquid/sand and the gas/liquid/sand flows.

Danielson (2007)'s MTC correlation for liquid/solid flows was developed considering the pipe inner diameter and properties of solid and fluid. The critical assumption of the theory is that there is a slip velocity between the liquid velocity and the sand velocity and that the slip velocity would remain relatively constant over a wide range of liquid velocities. Based on this assumption, the correlation for single phase could be written as:

$$U_C = K \nu^{-\frac{n}{2-n}} \mathrm{d}^{\frac{n}{2-n}} \big(gD(s-1)\big)^{\frac{1}{2-n}} \tag{7}$$

The best fit to experimental data gives $K = 0.23$ and n = 1/5. This correlation is dimensionally consistent in terms of velocity.

From what has been reviewed here, it can be seen that the predictions of sand transport are mainly based on two approaches. The first is focused on analysing forces on single particles (gravity, lift, drag forces and buoyancy) which could roll the particle downstream. The other approach is based on the theory of turbulence which is energy dissipated from turbulent eddies. Both approaches result in similar models.

2.2 MTC Models in Gas/Liquid/Sand Flows

The MTC models involving liquid/gas/sand have also been reviewed during this study, and a few of the typical models are briefly introduced below.

- **King, Fairhurst and Hill (2001) Model (referred as KFH model)**

King et al. developed a model based on the concept of minimum pressure gradient. This model is an extension from the Thomas (1962) minimum transportation condition prediction in single phase to two-phase MTC prediction, as shown in Section 2.1. After the friction velocity is obtained using Thomas correlations, the friction pressure drop at MTC could be calculated using:

$$\left|\frac{\Delta P}{\Delta x}\right|_{MTC} = \frac{4\rho_l({u_c}^*)^2}{D} \tag{8}$$

where ${u_c}^* = (f/2)^{0.5}V_C$ is the friction velocity corresponding to the MTC critical velocity. In two-phase gas-liquid pipelines, if the pressure drop calculated using Beggs & Brill correlations is greater than the pressure drop at MTC, particles would be transported.

- **Yan (2010) Model**

Yan developed a new correlation for friction velocity in his paper which is an extension of the KFH model. Two correlations were used to differentiate the effects of particle volume concentration, as follows:

$$u_c^* = u_o^* + 0.7176{C_v}^{0.5099},\ \ C_v < 0.0005 \tag{9}$$

$$u_c^* = u_o^* + 0.0776{C_v}^{0.2032},\ \ C_v \geq 0.0005 \tag{10}$$

Then Equation (8) was used to calculate the critical pressure gradient for keeping sand particles in suspension in the liquid.

- **Oudeman (1993) Correlation**

Oudeman developed his correlation based on a series of experimental data. In his model, he created two dimensionless parameters: the sand transport rate φ_S and the fluid flow rate Ψ_L.

$$\varphi_S = \frac{S'}{\sqrt{{d_p}^3 g(s-1)}} \tag{11}$$

$$\Psi_L = \frac{{U_b}^2}{g d_p(s-1)} \tag{12}$$

where S' is the transport rate which could be defined as volume of sand transported per second per sand bed width in metres. U_b is the fluid drag velocity. The sand transport rate φ_S could be described as a function of the fluid flow rate Ψ_L.

$$\varphi_S = m{\Psi_L}^n \tag{13}$$

where the values of *m* and *n* are determined by experiments which are related to the gas fraction. Values of m and n as a function of gas fraction are shown in Table 1.

Table 1: Values of m and n as functions of gas fraction (%)

GAS FRACTION (%)	VALUE OF *m*	VALUE OF *n*
0	220	3.6
10	75	2.8
20	67	2.5
Average of 10 and 20	70	2.7

- **Gillies (1997) Correlation**

Gillies et al. extended the Meyer-Peter (1948) single phase model to two phase using dimensionless parameters similar to Oudeman.

$$\varphi_s = \frac{q_s}{s\sqrt{{d_p}^3 g(s-1)}} \tag{14}$$

$$\Psi_L = \frac{\rho_l g d_p (s-1)}{\tau_0} \tag{15}$$

$$\varphi_s = \left[\frac{4}{\Psi_L} - 0.188\right]^{1.5} \tag{16}$$

where q_s is the sand volume flow rate per sand bed width.

- **Danielson (2007) Model**

The assumption on which this MTC model was developed was the same as that in liquid/sand flows. Sand transport is due to slip velocity theory between the liquid and the sand. In multiphase flow, the gas phase is not a direct factor that influences the sand transport. The method used to calculate multiphase flow conditions in his paper is to equate the critical velocity in single phase to that in the multiphase flows. Danielson adopts Samala's (2000) correlation, i.e. Equation (6), for calculating the critical mixture velocity V_C above which sand would be transported. In order to apply the correlation, V_{sL}/V_m, the ratio between liquid superficial velocity and mixture velocity of multiphase flows, must be resolved. One simple and commonly used model to describe the relationship between the gas velocity and the mixture velocity is the drift flux model which was first proposed by Nicklin et al. (1962).

$$V_g = CV_M + V_o \tag{17}$$

where V_g is the gas velocity. $C = 1.2$ when the flow regime is intermittent flow, $C = 1$ when the flow regime is stratified flow. V_o is the bubble rise velocity.

$$V_o = 0.4\sqrt{1 - \frac{\rho_g}{\rho_l}}\sqrt{gD} \text{ , for intermittent flow} \tag{18}$$

$$V_o = V_{sl}\sqrt{1-\frac{\rho_g}{\rho_l}} \text{ , for separated flow} \tag{19}$$

Assuming the liquid holdup H_l is known, the liquid velocity can be obtained by using:

$$V_l = V_{sl}/H_l \tag{20}$$

The overall hold-up H_o is calculated as

$$H_o = H_l + H_s \tag{21}$$

where H_s is the sand hold-up, usually a very small value. In this MTC, instead of the local liquid velocity V_l , Danielson considered the slip velocity $(V_l - V_s)$, where V_s is the sand velocity. Thus,

$$V_c = V_{sl}/(H_o - H_s) - V_{ss}/H_s \tag{22}$$

or

$$V_c {H_s}^2 + (V_{sl} + V_{ss} - V_c H_o)H_s - V_{ss}H_o = 0 \tag{23}$$

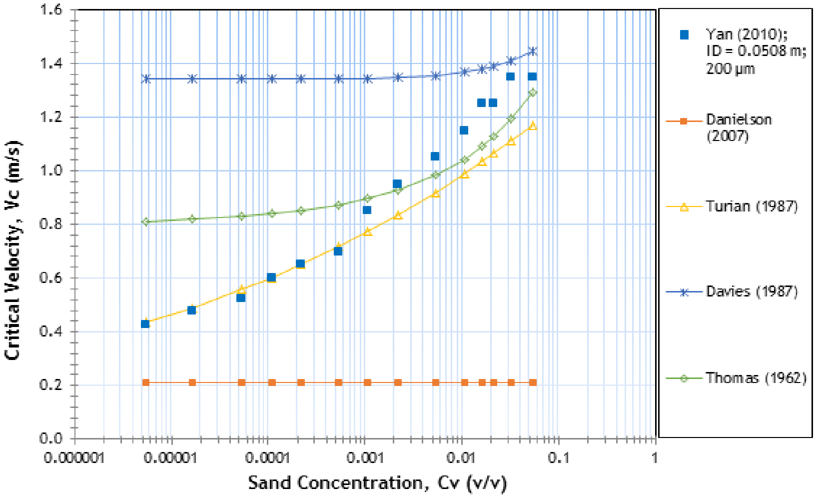
where V_{sl} and V_{ss} are the liquid and sand superficial velocities respectively. Combining the Equations (6) and (17-23), the critical velocity can be obtained.

To our knowledge, the Danielson model and KFH models are widely used in the oil and gas industry for the initial screening of sand deposition risk in pipelines; thus, in this study the models (including the modified models) were selected to be benchmarked against the published experimental data.

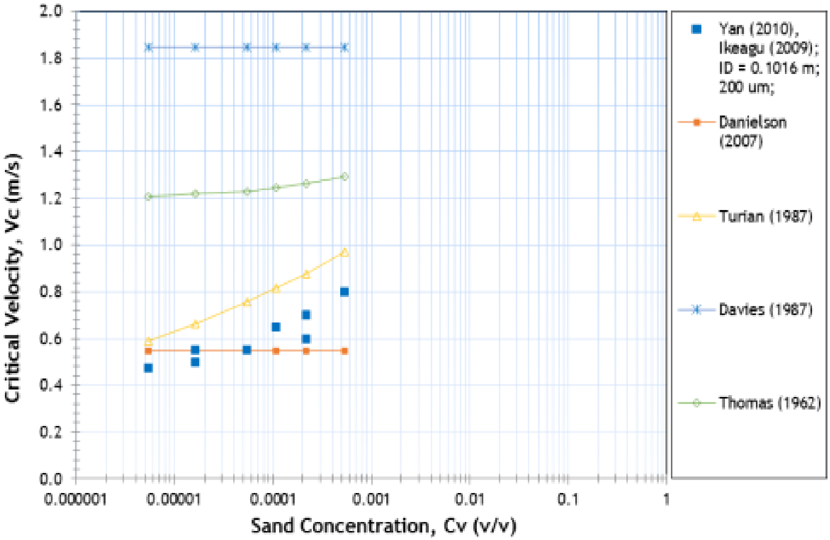
3 RESULTS

3.1 Liquid/Sand Flows

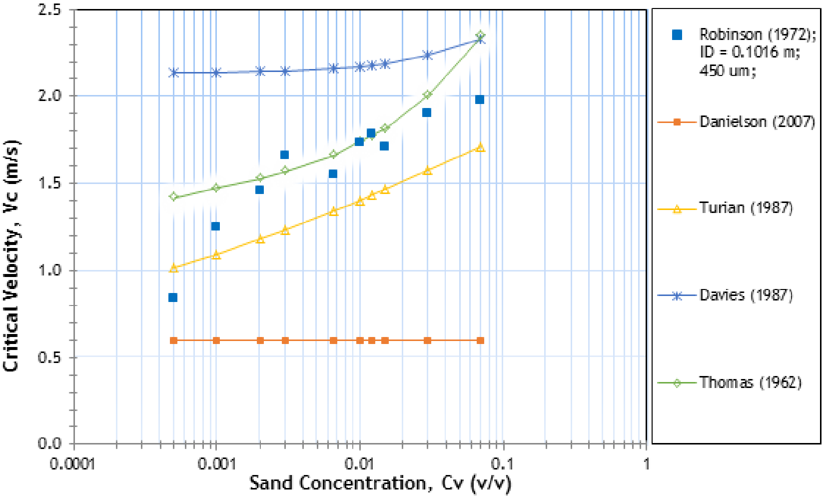
Typical MTC correlations for liquid/sand flows were compared. Two experimental datasets chosen for benchmarking were Yan (2010) and Robinson (1972). Yan (2010) data includes the results from the tests in a 2-inch pipe with sand concentrations varying from 5 lb/1000bbl (~5 ppm v/v) to 50 lb/bbl (~0.05 v/v) and in a 4-inch pipe with sand concentrations also varying from 5 lb/1000bbl (~5 ppm v/v) to 50 lb/1000bbl (~50 ppm v/v). The particle nominal size was 200 µm. Robinson's (1972) data includes the results from tests in a 4-inch pipe with nominal particle sizes of 450 µm and 880 µm; the sand concentration ranges were 5 to 650 ppm v/v and 0.0012 to 0.05 v/v, respectively.



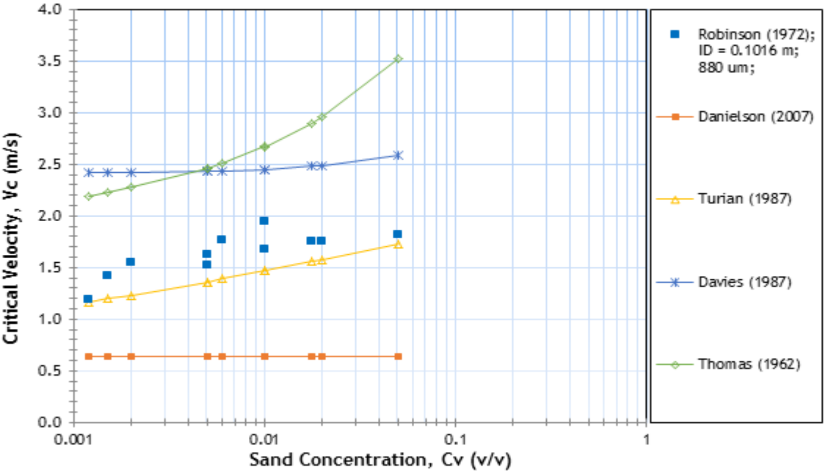
a) Models vs. Yan (2010), 2-inch i.d., sand nominal size of 200 µm



b) Models vs. Yan (2010), 4-inch i.d., sand nominal size of 200 µm



c) Models vs. Robinson (1972), 4-inch i.d., sand nominal size of 450 µm



d) Models vs. Robinson (1972), 4-inch i.d. sand nominal size of 880 µm

Figure 1: Comparisons between the predicted MTC and experimental results

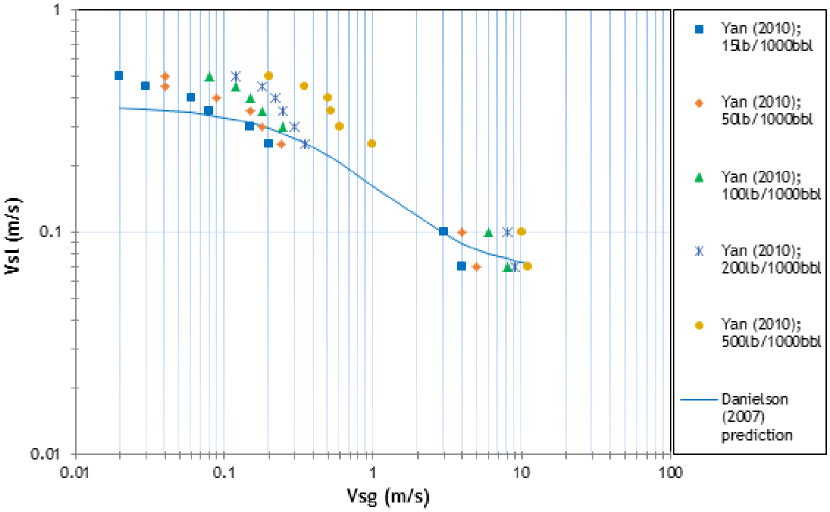
As sand concentration is an important factor which influences the transport velocity and it is the main variable in the experiments, it was chosen to be the horizontal axis. Figure 1 (a) and Figure 1 (b) show the comparisons between the predictions by different MTC models and Yan (2010) data. Figure 1 (c) and Figure 1 (d) show the comparisons between the MTC model predictions against Robinson (1972) data.

With regard to the experimental data above, the prediction performance of MTC models can be assessed by examining the plots in Figure 1 using the 'mean square error' method which indicates the level of deviation of predictions. Overall, the Turian (1987) correlation gives the best fit with regard to all of the test data sets. The Thomas (1962) correlation was consistent with experimental data but has a larger deviation than that of Turian (1987). It has no specific term for concentration factor but the prediction still varies against the particle concentration, due to settling velocity being included in the model. The Davies (1987) correlation changes fairly gradually with the solid concentration. The Danielson (2007) correlation has no factor related to solid concentration; thus, the prediction stays at a constant value.

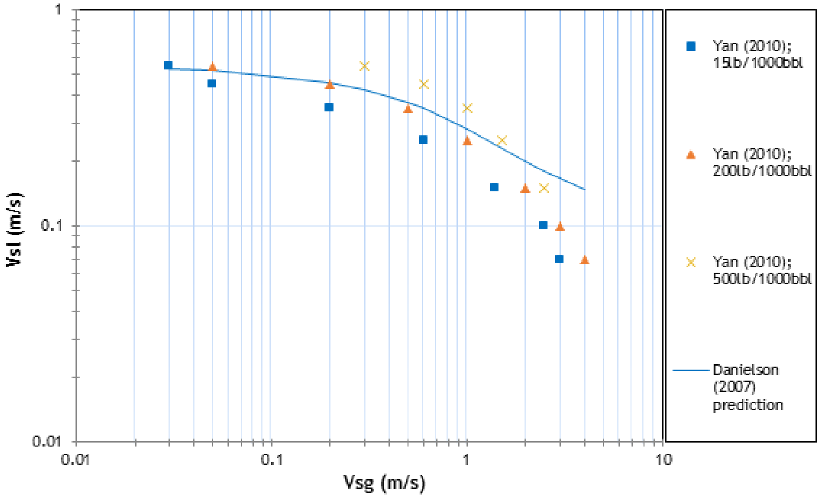
3.2 Gas/Liquid/Sand Flows

3.2.1 Danielson (2007) MTC model

The datasets chosen to evaluate the performance of the Danielson (2007) model were those from Yan (2010) and Najmi (2015). Yan’s data covers 2-inch and 4-inch pipes with sand concentrations varying from 15 lb/1000bbl (~15 ppm v/v) to 500 lb/1000bbl ((~500 ppm v/v); the nominal particle size was 200 microns. Najmi’s data includes 2-inch and 4-inch pipes with sand concentrations varying from 0.01% to 0.1% (v/v) in volume fraction; the nominal particle size was 300 microns. The comparison between the predicted results and Yan’s experimental results are shown in Figures 2. Likewise the comparison between the predicted results and Najmi’s experimental results are shown in Figures 3. Since Danielson’s model omitted the effect of sand concentration, the test data presented in each figure cover different sand concentrations.



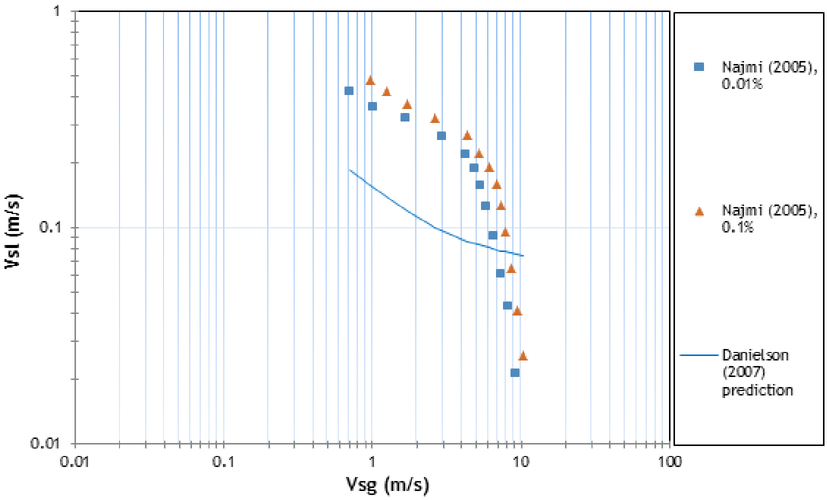
a) Tests of 2 inch pipe with sand nominal size of 200µm



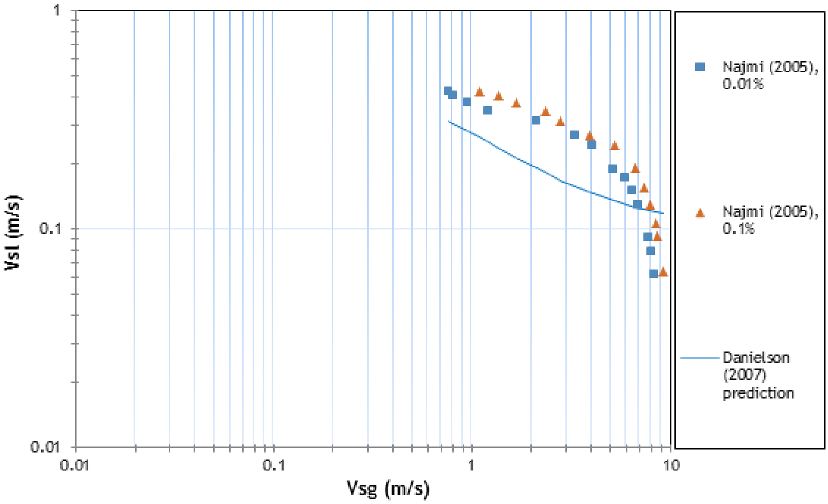
b) Tests of 4 inch pipe with sand nominal size of 200µm

Figure 2: Danielson's prediction vs. Yan (2010) experimental results

The correlation of gas and mixture velocities in the intermittent flow regime was used. It can be seen from the plots that the trend of Danielson's prediction is gentle when the gas superficial velocity is low and then begins to decline more sharply when the gas superficial velocity increases. When it increases further, the curve becomes gentle again. The model gives reasonable predictions compared to Yan (2010) data. However, the prediction performance is less satisfactory when compared to Najmi's data. This is potentially owing to the difference in the definition of sand transport conditions. Yan (2010)'s definition was "preventing the formation of a sliding sand layer", where Najmi's definition was "all particles are moving in suspension". In nature, sand transportation observed by Najmi should be higher than that by Yan at similar conditions. Yan's data mainly focused on the intermittent flow regime with the gas superficial velocity for the majority of points staying below 4 m/s. This is exactly the correlation mentioned in Danielson (2007). Najmi's data points mainly stay above the gas superficial velocity of 4 m/s which enters a separated flow regime and correlations for intermittent flow is not suitable.

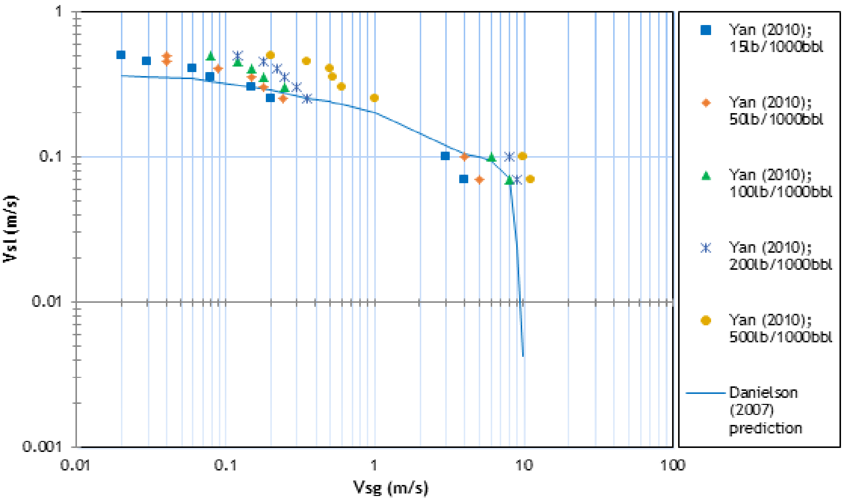


a) Tests of 2 inch pipe with sand nominal size of 300μm

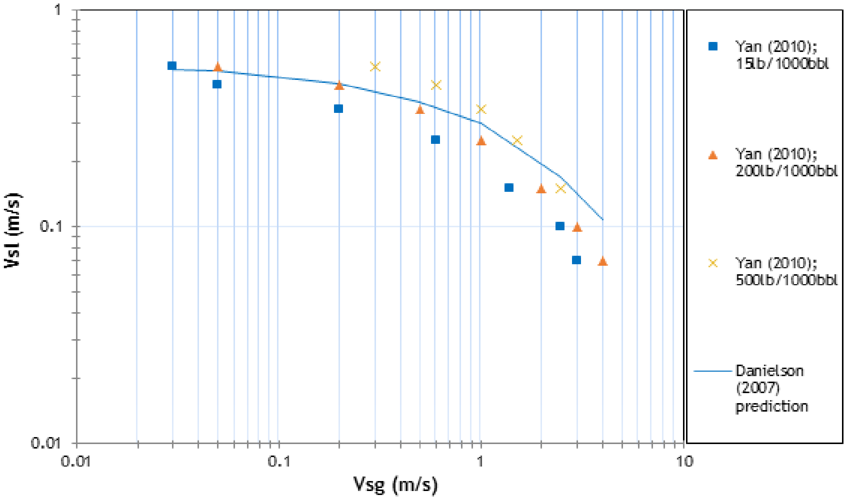


b) Tests of 4 inch pipe with sand nominal size of 300μm

Figure 3: Danielson’s prediction vs. Najmi (2015) experimental results

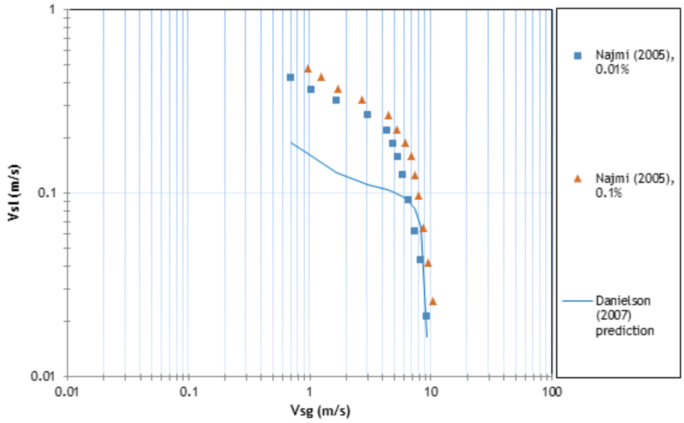


a) 2 inch, 200 µm experiment

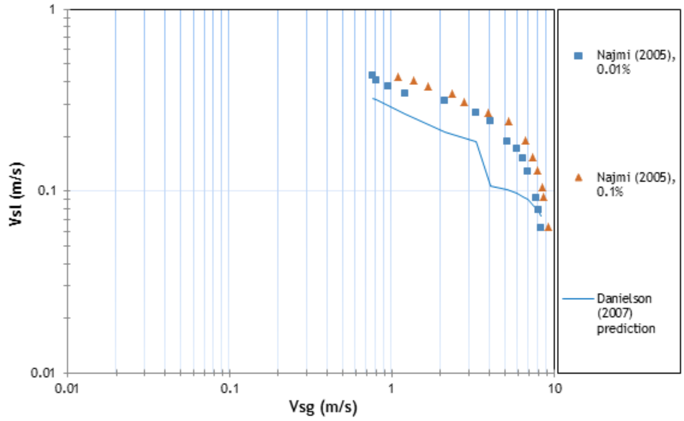


b) 4 inch, 200µm experiment

Figure 4: Extended Danielson's prediction vs. Yan (2010) experimental results



a) 2 inch, 300 μ m experiment



b) 4 inch, 300μm experiment

Figure 5: Extended Danielson's prediction vs. Najmi (2015) experimental results

An extension to the Danielson model proposed by Najmi et al (2016) was to apply the correlation, Equation (19), for the separated flow regimes. Annular flow is one of the separated flow regimes with high gas rates, thus the extended Danielson model is used, and the results are presented in Figures 4 and 5. The extended Danielson model gives an improved prediction performance when compared with the Yan (2010) and Najmi (2015) test data, when at high superficial gas velocities.

Data gathered from both Yan (2010) and Najmi (2015) are focused on low sand concentration, Danielson's extended model can be considered to have a good prediction performance for general low concentration conditions.

3.2.2 KFH models

For comparison, experimental data identical to that compared with the Danielson Model are also used to benchmark the KFH models, which include both the original KFH model and two modified KFH models as follows: (1)Yan (2010) model (a modified KFH model by $u_c{}^*$ calculated using Equations (9) and (10); (2)Turian (1987) based model (a modified KFH model by $u_c{}^*$ calculated using $u_c{}^* = (f/2)^{0.5}V_C$ in combining with Equation (4)).

Table 2: Mean discrepancy[1] between the predicted results of KFH model, Yan (2010) model, Turian based KFH model and Danielson model against the benchmark data sets

Datasets	Test Conditions	KFH Model	Yan's Model	Turian Based Model	Danielson Model
Yan (2010), 200μm	2-inch, 15 lb/1000bbl	0.2817	0.2091	0.1937	0.1584
	2-inch, 50 lb/1000bbl	0.4562	0.3141	0.2657	0.2094
	2-inch, 100 lb/1000bbl	1.0884	0.7888	0.7092	0.0831
	2-inch, 200 lb/1000bbl	1.2898	0.8863	0.8253	0.2991
	2-inch, 500 lb/1000bbl	1.7530	1.0418	1.0893	0.7130
	4-inch, 15 lb/1000bbl	0.1435	0.0549	0.2235	0.4022
	4-inch, 200 lb/1000bbl	0.3702	0.0198	0.5051	0.3064
	4-inch, 500 lb/1000bbl	0.3914	0.0270	0.2384	0.1019
AVERAGE		**0.7218**	**0.4177**	**0.5063**	**0.2842**
Najmi (2015), 300μm	2-inch, 0.01%	2.6293	2.0308	1.3795	0.7610
	2-inch, 0.1%	3.3645	2.0308	1.3795	1.0787
	4-inch, 0.01%	2.4828	2.0015	0.8189	0.7221
	4-inch, 0.1%	3.1061	1.2233	0.5689	1.3499
AVERAGE		**2.8957**	**1.8216**	**1.0367**	**0.9779**

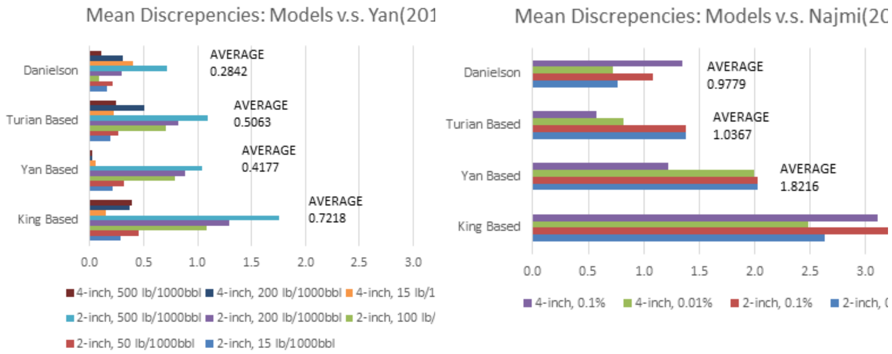
The results of the mean discrepancy between the benchmark data sets and the predictions using the KFH models, including the extended Danielson's model, are illustrated in Table 2 and Figure 6. For the convenience of comparison, the mean discrepancies between the benchmark data sets and the predictions using the extended Danielson model are also illustrated in Table 2 and Figure 6.

From the comparisons above, Danielson's model demonstrated a good prediction performance in general. As for the other three, Yan's model and the Turian based KFH

---

[1] The mean discrepancy is defined as the square root of the standard deviation resulted from the differences between model predictions and test results.

model performed fairly well when compared to the Yan (2010) data. Yan’s model is slightly better because as this model was based on his own data. When compared to Najmi’s data, the distinctive difference of mean discrepancies demonstrated that the Turian based KFH model was the best. The comparison with Yan’s data illustrates that Yan’s model and the Turian correlation-based KFH model are both applicable for industry prediction.



a) Yan (2010)’s datasets b) Najmi (2015)’s datasets

Figure 6: Mean discrepancy between the predicted results of KFH model, Yan (2010) model, Turian based KFH model and Danielson model against the benchmark datasets

4 CONCLUSION AND RECOMMENDATION

This paper has reviewed typical existing MTC models in liquid/sand flows and gas/liquid/sand flows. Four liquid/sand models, including the Danielson (2007) correlation, the Turian et al (1987) correlation, the Davies (1987) correlation and the Thomas (1962) correlation, were selected for assessment. Yan (2010) data and Robinson (1972) data are used for benchmarking. The Turian et al (1987) correlation appeared to have the best performance. In gas/liquid/sand flows, the Danielson (2007) model and the KFH models, including the Yan (2010) model and the Turian correlation-based model, were selected to be evaluated against the test datasets by Yan (2010) and Najmi (2015). It appeared that the Danielson model demonstrated the best performance in terms of average discrepancy against the benchmark datasets.

It is worth noting that the sand transport conditions observed in experiments depend on the definition of sand transport conditions used by different researchers. Both Danielson’s model and the Turian correlation-based KFH model demonstrated a reasonable prediction of sand transport conditions in multiphase flow as compared to existing experimental data. It is also interesting to note the following differences regarding the models: a). Danielson’s model is based on the assumption that the slip velocity between the liquid and the particle would remain relatively constant for a wide range of liquid velocities, while the KFH model uses the minimum pressure drop assumption; b). In Danielson’s model, the flow regime needs to be determined (e.g. with Taitel and Duckler method) prior to using the sand transport model; then different drift velocity calculation methods can be applied accordingly for sand transport velocity calculation, while with KFH model (or the modified version), the flow regime was obtained from the Beggs and Brill correlation, which is essentially based on Froude number criteria. Nonetheless, both models appear good for being used as initial screening tools to determine sand deposit-free pipeline operating conditions. The Turian correlation-based KFH model provides more flexibility for model tuning and field data matching, owing to its fundamental "energy equivalency" concept.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Wei Yan, Petrofac Ltd, for the helpful advices and discussions during this study.

REFERENCES

(1) Al-lababidi, S., Yan, W., and Yeung, H., 2012, "Sand Transportation and Deposition Characteristics in Multiphase Flows in Pipelines," ASME Journal of Energy Resources Technology, 134(3), pp. 1–13

(2) 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.

(3) 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.

(4) Beggs, H. D. and Brill, J. P., (1973), "A Study of Two-Phase Flow in Inclined Pipes", J. Pet. Tech., pp. 607-617

(5) Blatch, N.S., 1906, "Discussion of 'Works for the purification of the water Supply Washington D.C.'", Trans Amer. Soc. Civil Engrs., Vol.57, pp. 400-409.

(6) Charles, M. E., (1970), "Transport of Solids by Pipelines", Hydrotransport 1, pp. A3-A25.

(7) Condolios, E. and Chapus, E. E., (1963), "Transporting Solid Materials in Pipelines", Chem. Eng., Vol. 24, pp. 93-98.

(8) Davies, J.T., (1987), "Calculation of Critical Velocities to Maintain Solids in Suspension in Horizontal Pipes", Chem. Eng. Sci, Vol. 42, 7, pp. 1667-1670.

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

(10) Durand, R. and Condolis, E., 1953, "Basic Relationships of the Transportation of Solids in Pipes—Experimental Research," The Minnesota International Hydraulics Convention, University of Minnesota, Minneapolis, MN, pp. 89–103.

(11) Fairhurst, C. P. & Baker, P. J., (1983), "Multiphase Sand Transport in Oil Production Flowlines", Draft report on BHRA Project RP D00935, BHRA, Cranfield, Bedfordshire, UK.

(12) Friedel L., (1979), "Improved Friction Drop Correlations for Horizontal and Vertical Two-Phase Pipe Flow", European Two-Phase Flow Group Meeting, paper E2, Ispra, Italy.

(13) Gillies, R.G., McKibben, M.J. and Shook, C.A. (1997), "Pipeline Flow of Gas, Liquid and Sand Mixtures at Low Velocities", J.Can.Pet.Tech, Vol. 36, pp. 36-42.

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

(15) King, M.J.S., Fairhurst, C.P. and Hill, T.J., (2001), "Solids Transport in Multiphase Flows Application to High Viscosity Systems", Energy Sources Tech Conf, New

Orleans, pp. 14-17.

(16) Kokpinar, M.A., and Gogus, M., (2001), "Critical Flow Velocity in Slurry Transporting Horizontal Pipelines", Journal of Hydraulic engineering, Vol. 127, pp. 763-771.

(17) Lockhart R.W., Martinelli R.C., (1949), "Proposed Correlation of Data for Isothermal Two-phase Two-component in Pipes", Chem. Eng. Process, Vol. 45, pp. 39–48.

(18) Meyer-Peter, E. and Müller, R., (1948), "Formulas for Bed-load Transport", Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research, pp. 39-64

(19) Najmi, K, Hill, A.L., McLaury, B.S., Shirazi, S. A. and Cremaschi, S. (2015), "Experimental Study of Low Concentration Sand Transport in Multiphase Air–Water Horizontal Pipelines", Journal of Energy Resources Technology 137(3), pp. 032908-1–032908-10

(20) Najmi, K, McLaury, B.S., Shirazi, S. A. and Cremaschi, S. (2016), "Low concentration sand transport in multiphase viscous horizontal pipes: An experimental study and modeling guideline", AIChE Journal, Vol. 62, pp. 1821–1833

(21) Nakayama, Y.; Boucher, R.F., ―Introduction to Fluid Mechanics, Elsevier, 2000

(22) Nicklin, D.J., Wilkes, J.O., and Davidson, J.F., "Two-Phase Flow in Vertical Tubes," Trans. Instn. Chem. Engrs., Vol. 40, pp. 61-68, 1962.

(23) Oroskar, A. R., and Turian, R. M., (1980), "The Critical Velocity in Pipeline Flow of Slurries", AIChE Journal, Vol. 26, pp. 550-558.

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

(25) Robinson, M.P., Graf, W.H., 1972, "Critical Deposit Velocities for Low-Concentration Sand Water Mixtures," ASCE National Water Resources Engineering Meeting, January 24-28.

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

(27) Salama, M. M., and Venkatesh, E. S., (1983), ''Evaluation of API RP 14E Erosional Velocity Limitations for Offshore Gas Wells" Proc., 15th Offshore Technology Conference, Paper OTC 4485

(28) Stevenson, P., Thorpe, R.B., Kennedy, J.E. and McDermott, C., (2001a), "The Similarity of Sand Transport by Slug Flow and Hydraulic Conveying", Proceedings of 10th Int. Conf. on Multiphase Flow, BHRA, France, pp. 249-260.

(29) Thomas, D.G. (1962), "Transport Characteristics of suspensions Part VI. Minimum Transport Velocity of Large Particle Size Suspensions in Round Horizontal Pipes", AIChE J., Vol. 8, 3, 373-377.

(30) Thomas J. Danielson, (2007), "Sand Transport Modeling in Multiphase Pipelines", Offshore Technology Conference, OTC paper 18691.

(31) Wasp, E.J., Aude, T.C., Kenny, J.P., Seiter, R.H., Jacques, R.B., (1970), "Deposition Velocities, Transition Velocities and Spatial Distribution of Solids in Slurry Pipelines", Proceedings of Hydrotransport 1, BHRA Fluid Engineering, Cranfield, Bedford, England, Paper H4.

(32) Yan, W. (2010), "Sand Transport in Multiphase Pipelines", PhD Thesis, Department of Process and Systems Engineering, Cranfield University, UK.

(33) 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.101-123.