Membership

BP
BHP
Chevron
Petrobras
Saudi Aramco
Petronas
Shell
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<th>TIME</th>
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<tr>
<td>9:00 – 9:10 a.m.</td>
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<td>TUSMP Activities and Deliverables</td>
<td>Ronald E. Vieira</td>
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<td>Sand Transport – Experiments and Mechanistic Model Advancements</td>
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<td>9:45 – 10:20 a.m.</td>
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<td>Asad Nadeem</td>
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<tr>
<td>11:30 – 12:00 p.m.</td>
<td>Industry Presentation &amp; Open Discussion and Planning</td>
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</tr>
<tr>
<td>12:00 – 1:00 p.m.</td>
<td>Lunch</td>
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Spring 2022 Meeting Date: May 26, 2022  
Fall 2022 Meeting Date: November 10, 2022  
These are proposed dates. Check website for updated info. [http://www.tusmp.utulsa.edu/events.html](http://www.tusmp.utulsa.edu/events.html)
Executive Summary of TUSMP Presentations

The following is the executive summary of presentations at the TUSMP meeting on November 11, 2021.

**Sand Transport – Model Enhancements in Horizontal/Inclined Wells and Pipelines**

Dr. Ronald Vieira, Research Associate

Sand is often produced out of the reservoir in both onshore and offshore production systems. The deposition of sand poses several risks, including increased frictional pressure losses, increased risk of corrosion, and increased risk of equipment failure. Prediction of the critical flow rate in multiphase flow is a serious concern of multiphase production. Over the last decades, many researchers investigated particle flow physics experimentally and tried to predict the flow physics either empirically or mechanistically. They were able to develop models to predict the critical velocity for sand to keep moving in individual flow regimes such as stratified or slug flow. However, there is not a single unified model that can predict the critical velocity required to transport the sand particles without stopping under different mechanisms. The major goal of this project is to develop a mechanistic model to predict the minimum flow rate (critical flow rate) required to constantly move the sand particles in single and multiphase flow under different flow patterns.

The current work includes an experimental study to expand the current database for critical flow rates to transport sand in sand–water and sand–air–water flows. At this time, experiments are being performed with water in 2-inch inclined pipes (5° upward). Four different particle sizes (25, 75, 150 and 300 µm) and seven different volume concentrations of particles (from 100 to 5000 ppm) are being used. Experimental data shows that critical velocity is a function of sand concentration. For sand-water flow, when compared with previous data in horizontal flow, small differences in sand transport velocities were detected when the pipe was tilted up to 5°. Comparison of obtained data with a modified TUSMP model results shows that the model can accurately predict critical flow rates for medium particles size while slightly underpredicting sand transport for small particles.

It was also observed that in sand–air-water flow the transport characteristics of sand particles changed significantly by changing the pipe inclination. As in a horizontal pipeline, the critical transport velocities in sand-air-water flows in inclined pipelines are flow regime dependent. For inclined pipelines, the slugs and pseudo-slugs were found more prevailing. It was observed that sand particles transport more efficiently in plug and slug flow in 5° inclined pipes when compared to previous results obtained in horizontal pipes for similar conditions. The sand transport and settling boundary for different air–water flow regimes, sand concentrations and sand sizes were generated for the inclined pipeline.
The TUSMP sand transport model is currently being expanded and tested to include the effect of the inclination angle. Furthermore, work is in progress to test this model against larger pipe diameters to improve it. Finally, the mechanistic model is being developed into a design code (Microsoft Excel interface) that can be used by the industry.

**Acoustic Sand Monitors for Multiphase Flow Systems: Experimental Study**  
Asad Nadeem, PhD Student, Mechanical Engineering

The effect of solid particle erosion in the oil and natural gas industry can be detrimental to pipes and equipment, which can lead to production shutdown and other economic losses. A broad range of operating conditions has been investigated in the past using acoustic sand detectors at TUSMP to determine the effectiveness of sand monitoring in multiphase flow. Those experiments have been performed while varying superficial gas and liquid velocity, sand size, pipe diameter, liquid viscosity, and flow orientation. Past program objectives have been to find the variation in Threshold Sand Rate (TSR) for different multiphase flow regimes and orientations for different pipe diameters using the 1, 2, 3 and 4-inch multiphase flow loops for the ClampOn DSP-06 monitors using 25 µm through 300 µm sand. TSR is defined as the minimum sand rate necessary to achieve monitor output higher than the background noise level. In other words, it is at this level that the monitor begins to differentiate the background noise from the sand noise level.

The main objective of this work is to use the Acoustic Sand Monitors for vertical and horizontal multiphase flows in 2-inch, 3-inch and 4-inch pipes and to determine the Threshold Sand Rate. The experiments were performed for liquid-only, slug, stratified-wavy, dispersed-bubble, churn and annular flow in vertical and horizontal orientations. The present research focuses on the use of 25 µm, 75 µm, 150 µm, 300 µm, and 600 µm sand particles and 50 µm glass beads. A recirculating or once-through injection was implemented depending on the specific flow condition. Two types of two different acoustic sensors were used, ClampOn (DSP-06) and Roxar (SAM 400 TC Model) in different test sections utilizing gas dominated (3-inch) and liquid dominated (2-inch and 3-inch) flow loops. Due to the flow regime effect, investigations related to the calculation of TSR are of great interest. When the results of both high superficial liquid velocity and low superficial liquid velocity are compared, it can be found that the TSR is higher in the experiment with high superficial liquid velocity. When the results of ClampOn and Roxar monitors are compared, it is observed that ClampOn is more sensitive than Roxar especially in slug flow regimes and low-liquid velocities.

Future work will include testing both acoustic monitors for annular-mist flow conditions for 3-inch and 4-inch pipes with horizontal and vertical orientations with 50 µm glass beads. Future work will also include more liquid dominant experiments with water as well as a few experiments with gas-liquid in dispersed-
bubble and slug flow. Development of correlation of Calibration factor using TUSMP Acoustic Program is also included in future plan.

Utilizing Artificial Intelligence for Determining Threshold Sand Rates from Acoustic Monitors
Jamie Li, PhD Student, Computer Science

Acoustic sand monitors are non-intrusive passive devices and they can be used to provide a warning when sand is being produced in pipelines and/or determine sand rates when calibrated. These devices are attractive to be installed on individual wells or manifolds to detect sand production in offshore production units. One drawback of such devices is the noise created by flow impacting the pipe walls. Thus, if the impact speed or the rate of sand is low, the monitor will not be able to recognize/differentiate the noise that is generated. The minimum sand rate that can be recognized by the monitor is called a Threshold Sand Rate (TSR). A significant amount of data has been compiled over the years for TSR for various flow conditions, pipe sizes and sand sizes. However, it has become challenging to use this data to develop a theoretical model for different flow rates and sand sizes. The goal of this project is to design an Artificial Intelligence (AI) approach to determine TSR. The acoustic sand monitor data utilized in this work has been generated mostly in the lab for sand sizes ranging from 20 to 600 microns varying sand concentrations and pipe diameters 2, 3 and 4 inches in vertical and horizontal directions downstream of elbows. The database has been expanded from 237 to 298 cases including three new flow patterns: Stratified Flow, Gas-Only and Liquid-Only. The TSR data, pipe diameter, particle size, inclination, superficial liquid/gas velocity, mixture density/viscosity, and flow regime has been used to train and create an AI model that can predict TSR for different flow conditions. Moreover, mean values and standard deviation of background noise levels are included as input variables and are tested as a parameter along with other flow variables. The parameters of the AI models, including Elastic Net (ENET), Random Forest (RF), Support Vector Machine (SVM), and eXtreme Gradient Boosting (XGBoost) are optimized using nested cross-validation and the model performance is evaluated by R-squared.

The average R squares (test set) for 95% Confidence TSR prediction using ENET, RF, SVM and XGBoost models are 0.64, 0.71, 0.84, and 0.76, respectively. The models agreement with experimental data is encouraging and suggests that this model can be extended for a variety of flow conditions and pipe sizes not tested before. This project delivers and provides significant TSR data, a framework describing a novel methodology to utilize Artificial Intelligence to correlate the TSR with pipe size, sand size, inclination, superficial liquid/gas velocities, mixture density/viscosity, flow regime, and background noise levels.

Acoustic Sand Monitors for Multiphase Flow Systems: Modeling Study
Asad Nadeem, PhD Student, Mechanical Engineering

The online measurement of the solid phase in multiphase flows is significant in industrial production processes, especially for oil production in old oilfields. One
of the attractive methods for sand detection is utilizing commercially available acoustic sand monitors that clamp to the outside of pipe wall and presumably detect noise from sand impact with the pipe wall. Operators are very interested in these monitors, but the effectiveness of these monitors to detect and distinguish sand impact noise from the background flow noise in multiphase flow is questionable. The objective of this work is to utilize laboratory and field data to determine threshold sand rates that these acoustic detectors can effectively detect. To improve the existing limitations in the detection of dilute solid particles in solid-gas–liquid conveying systems, Threshold sand rate (TSR) is frequently used for sand management in production systems.

A computer program called "Acoustic" was originally developed in TUSMP to allow users to calibrate their acoustic sensors given that they know the fluid conditions, sand rate, monitor output, and background noise. The Acoustic model predicts the correct trend in monitor output as a function of sand rate. For that, an equation was developed to find a calibration factor (C) by inputting the flow conditions and sand rates. This equation was fitted using data and experimentation from 1-inch and 2-inch flow loops. Fits for C values and prediction of impact velocities allow the model to be used for a broad range of operating conditions from only one calibration point. The model also depends on impact velocities predicted by SPPS (two approaches available).

In this work, the Acoustic Program is used to calculate the sand rates for some of the most recent TUSMP acoustic experiments for liquid-dominated and gas-dominated flows in 2 and 3-inch I.D. pipes. The program is also used to predict TSR values using a given sand rate, background noise value and its standard deviation ($2\sigma$). The predicted values show good agreement with experimental values.

Future work will include the development of new correlations for C values. The final goal is to develop a semi-mechanistic model to predict TSR values by utilizing the data of all TUSMP experiments for different pipe diameters (1-inch to 4-inch), different flow regimes and different sand sizes.

**Artificial Intelligence for Sand Transport: Developments and Software Updates**

Dr. Ronald Vieira, Research Associate

Solids transport models are used to predict the fluid velocity required to transport solid particles in hydraulic and pneumatic systems. It is important that the processes in these applications are designed and operated at a sufficient fluid velocity to avoid solid deposition. Mechanistic models are used to provide a reasonable estimate for the minimum fluid velocity needed to transport the particles. However, those models are commonly applied in their respective ranges of data fitting; and are limited by the applicability of the empirically based closure relations that are a part of such models. Artificial Intelligence (AI) Machine learning (ML) offers a wealth of techniques to extract information from
data that can be translated into knowledge about the underlying fluid mechanics. The purpose of this work is to investigate the use of several ML models to predict the critical velocities of various single-phase carrier fluids in horizontal and inclined flow conditions. A framework is developed to predict critical velocities in pipes via ML, using accessible parameters as inputs, namely, fluid and particle properties and inclination angles. The ML algorithms are trained on a large dataset (more than 2000 data points) of critical velocities in single-phase carrier fluid that is collected from open source: articles and dissertations. The trained algorithms are Linear Regression, Random Forest, Support Vector Machine, and Extreme Gradient Boosting Decision Trees. Moreover, the influence of key features in critical velocity prediction was identified by the applied algorithms. Finally, the predictive abilities of the models are cross-compared and were further validated by comparing their performance with an expanded database for water-sand flows. The proposed ML approach is observed to a good performance across a wide range of flow conditions and inclination angles. The final objective of this work is to develop an Artificial Intelligence/ML model for predicting the critical velocity in multiphase flows.
TUSMP Activities and Deliverables

Ronald E. Vieira
Research Associate

Tulsa University Sand Management Projects
Mechanical Engineering Department
The University of Tulsa

November 11, 2021

TUSMP Meeting Agenda

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TUSMP Objectives

- Provide design and operating guidelines for sand transport, detection and measurements through TUSMP meetings, research results and computer programs:
  - Sand Transport Critical Velocity Predictor v7
    - Including a Machine Learning (Artificial Intelligence) calculation module based on more than 2000 data points
  - AI Software for Threshold Sand Rates (SPPS-TSR 1.0)
  - Acoustic (computer program for calibrating acoustic sand monitors)
  - Intrusive (calculates sand throughput corresponding to loss from an intrusive ER probe)

- Develop TUSMP Guidelines
  - Acoustic Sand Monitoring Guideline
    - Through experiments in medium and large scale flow loops
  - Sand Sampling Guidelines

TUSMP Past Activities

- Evaluate commercially available sand and erosion monitors
  - Acoustic monitors
  - Erosion monitors (ER probes, UT)
  - Optical devices

- Develop models and tools (computer programs) to help interpret output from sand and erosion monitors

- Determine critical flow rates necessary to transport sand
  - Perform experiments
  - Evaluate existing models and develop new models

- Develop guidelines for monitor use or methods used to obtain information on sand
Current / Future Research Scope

**Acoustic Sand Monitors (ASM)**
- Further investigate flows with smaller and intermediate particles (25, 50 and 75 µm)
- Examine performance of acoustic monitors:
  - ClampOn, Roxar
- Determine Threshold Sand Rates (TSR)
- Re-analyze raw data from previous investigations and extend current TSR database
- Extend experiments to liquid-dominated flows: liquid-sand, dispersed-bubble, slug flow
- Extend experiments to mist flow conditions (high gas - very low liquid flows)

**Acoustic Sand Monitor Modeling**

**Extend Acoustic Monitor Guideline**

**Development of Artificial Intelligence Model for Threshold Sand Rates (SPPS-TSR)**
- Continue tuning and improvement of evaluation scores of current models
- Implementation of new Machine Learning algorithms

**Sand Transport Study**
- Develop a predictive model for sand transport in horizontal and inclined pipes that includes two modules:
  - Mechanistic Model
  - Artificial Intelligence/Machine Learning
- Extend mechanistic models to account for the angle of inclination
- Develop AI Model for Multiphase Flow
  - Extend the single-phase flow model to Multiphase Flow
- Improve models to better account for scale-up of pipe diameter
- Improve models to better account for high liquid viscosity
- Performed experiments for inclined pipes with different sand sizes and viscosities
Sand Transport – Model Advancements in Horizontal/Inclined Wells and Pipelines

Ronald E. Vieira
Research Associate

Tulsa University Sand Management Projects
Mechanical Engineering Department
The University of Tulsa

November 11, 2021

Outline

- Objectives
- Activities since last ABM
- Critical velocity database expansion
  - New experiments in single-phase flow and multi-phase flow (Inclined pipe)
- TUSMP Sand Transport Model Development
  - Pipe inclination effect
  - Multiphase model development
- Future Work
Objectives

- Develop a mechanistic model to predict minimum flow rates required to constantly move sand for inclined pipes
- Conduct experiments for particle transport to expand current database
- Compare the mechanistic model with experimental and recent literature data for various operating conditions
- Improve user code and expand its applicability for multiphase calculations

Activities since last ABM

- Critical velocity database expansion
  - New experimental data for single-phase and multi-phase inclined flow:
    - Water-Sand Flow: 75 µm sand, 100–2000 PPM, Upward 5°
- Mechanistic model
  - Modified model for inclined flow (slug flow)
  - User code development
Critical Velocity Database Expansion

- The minimum velocity which demarcates flows in which the solids form a bed at the bottom of the pipe.

**Current Experimental Database**

**Single-Phase**
- Horizontal Flow: 1523 points (262 TUSMP, 1261 Literature)
- Inclined Flow: 478 points (28 TUSMP, 450 Literature)

**Multi-Phase**
- Horizontal Flow: 1596 points (915 TUSMP, 681 Literature)
- Inclined Flow: 321 points (128 TUSMP, 321 Literature)

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Critical Velocity Database Expansion

**TUSMP Experimental Facility for Inclined Flow**

- 2-inch I.D
- Air Capacity: 0.1 to 20 m/s
- Water capacity: 0.01 to 2.5 m/s

**Inclined Section**

- Observation Section
- \( \theta = 5^\circ \)
- 125 gallon tanks
- 54 and 18 gpm Pumps (Max. Capacity)

<table>
<thead>
<tr>
<th>Sand Size (( \mu m ))</th>
<th>Sand Vol. Concentration PPM</th>
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<tbody>
<tr>
<td>25</td>
<td>100–2500</td>
</tr>
<tr>
<td>150</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
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</tbody>
</table>
Critical Velocity Database Expansion

Flow Patterns Observed (Videos)

- Fully Dispersed
- Streaks
- Saltation
- Moving Dunes
- Stationary Dunes
- Sand Bed

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Critical Velocity Database Expansion

75 µm Sand Size Results

Sand Transport Velocities for 75 µm Sand; Water $\mu_{l} = 1$ cP;

<table>
<thead>
<tr>
<th>Sand Size (µm)</th>
<th>PPM</th>
<th>% v/v</th>
<th>$V_{C}$ (m/s)</th>
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<tr>
<td>75</td>
<td>100</td>
<td>0.010</td>
<td>0.550</td>
</tr>
<tr>
<td>75</td>
<td>250</td>
<td>0.025</td>
<td>0.578</td>
</tr>
<tr>
<td>75</td>
<td>500</td>
<td>0.050</td>
<td>0.610</td>
</tr>
<tr>
<td>75</td>
<td>750</td>
<td>0.075</td>
<td>0.671</td>
</tr>
<tr>
<td>75</td>
<td>1000</td>
<td>0.100</td>
<td>0.699</td>
</tr>
<tr>
<td>75</td>
<td>2500</td>
<td>0.250</td>
<td>0.756</td>
</tr>
<tr>
<td>75</td>
<td>5000</td>
<td>0.500</td>
<td>0.841</td>
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Exp. Data

$y = 0.3174x^{0.1122}$

$R^{2} = 0.9704$

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Critical Velocity Database Expansion
Summary of Single-Phase Results

Water $\mu = 1$ cP;

- 300 micron
- 150 micron
- 75 micron
- 25 micron

Critical velocity, m/s vs. Sand concentration, PPM

Critical Velocity Database Expansion
Experimental Matrix – Multiphase Flow

<table>
<thead>
<tr>
<th>Tests</th>
<th>$\theta$</th>
<th>Sand Size</th>
<th>Sand Conc.</th>
<th>$V_{SG}$</th>
<th>$V_{SL}$</th>
<th>Flow Pattern</th>
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<tbody>
<tr>
<td>(#)</td>
<td>(°)</td>
<td>(µm)</td>
<td>(PPM)</td>
<td>(m/s)</td>
<td>(m/s)</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>5</td>
<td>25–300</td>
<td>100–2000</td>
<td>0.06–1.17</td>
<td>0.14–0.89</td>
<td>Plug/Slug Flow</td>
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<tr>
<td>80</td>
<td>5</td>
<td>25–300</td>
<td>100–2000</td>
<td>0.12–7.92</td>
<td>0.12–0.32</td>
<td>Slug/Pseudo-Slug</td>
</tr>
</tbody>
</table>

$V_{SG} = 0.06$ m/s; $V_{SL} = 0.51$ m/s; 300mic; 100ppm

$V_{SG} = 3.96$ m/s; $V_{SL} = 0.20$ m/s; 75mic; 100ppm
Critical Velocity Database Expansion

Video Observations

\[ V_{SG} = 0.06 \text{ m/s}; \quad V_{SL} = 0.6 \text{ m/s}; \quad 300 \mu\text{m}; \quad 1000 \text{ ppm} \]

\[ V_{SG} = 3.5 \text{ m/s}; \quad V_{SL} = 0.32 \text{ m/s}; \quad 300 \mu\text{m}; \quad 1000 \text{ ppm} \]

Critical Velocity Database Expansion

Video Observations

\[ V_{SG} = 1.17 \text{ m/s}; \quad V_{SL} = 0.32 \text{ m/s}; \quad 300 \mu\text{m}; \quad 1000 \text{ ppm} \]

\[ V_{SG} = 2.33 \text{ m/s}; \quad V_{SL} = 0.27 \text{ m/s}; \quad 300 \mu\text{m}; \quad 500 \text{ ppm} \]
Critical Velocity Database Expansion
300 µm Sand Size Results

300 µm Sand

100 ppm  500 ppm  1000 ppm  2000 ppm

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

VSL, m/s

VSG, m/s

0  2  4  6  8  10

0.1

0.01

0  2  4  6  8  10

0.1

0.01

Dispersed Bubble
Slug
Liquid Loading
Annular
Wavy

θ

100 ppm  500 ppm  1000 ppm  2000 ppm

0.01

0.1

0  2  4  6  8  10

0.1

0.01

Dispersed-Bubble
Slug
Annular
Stratified-Wavy

θ

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Critical Velocity Database Expansion
150 µm Sand Size Results

150 µm Sand

100 ppm  500 ppm  1000 ppm  2000 ppm

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

VSL, m/s

VSG, m/s

0  2  4  6  8  10

0.1

0.01

0  2  4  6  8  10

0.1

0.01

Dispersed Bubble
Slug
Liquid Loading
Annular
Wavy

θ

100 ppm  500 ppm  1000 ppm  2000 ppm

0.01

0.1

0  2  4  6  8  10

0.1

0.01

Dispersed-Bubble
Slug
Annular
Stratified-Wavy

θ

Tulsa University Sand Management Projects
Critical Velocity Database Expansion
75 µm Sand Size Results

75 µm Sand

![Graph showing critical velocities for 75 µm sand at different concentrations of 100 ppm, 500 ppm, 1000 ppm, and 2000 ppm. The graph includes symbols for plug flow, slug flow, and pseudo-slug flow.]

Critical Velocity Database Expansion
25 µm Sand Size Results

25 µm Sand

![Graph showing critical velocities for 25 µm sand at different concentrations of 100 ppm, 500 ppm, 1000 ppm, and 2000 ppm. The graph includes symbols for plug flow, slug flow, and pseudo-slug flow.]

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Critical Velocity Database Expansion
Pipeline Inclination Effect

Comparison with Horizontal TUSMP Data
- Inclined, 100 ppm
- Inclined, 1000 ppm
- Horizontal, 100 ppm
- Horizontal, 1000 ppm

Cranfield Data (Yan, 2010)
- 2-inch, Inclined
- 2-inch, Horizontal
- 4-inch, Inclined
- 4-inch, Horizontal

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TUSMP Sand Transport Critical Velocity Predictor

- This is a computer software that can predict particle transport in wellbores and pipelines.
- Includes an Artificial-Intelligence-Machine Learning (AI-ML) calculation module based on more than 1600 data points.

Mechanistic and AI-ML Integration with Excel

Output: Mechanistic Unified Model Plot
Unified Model

Output for Single-phase transport cases

Output for Multi-phase transport cases

Tulsa University Sand Management Projects
**TUSMP Sand Transport Critical Velocity Predictor**

Single-phase Transport Module (Liquid-Solid and Gas-Solid)

\[
V = \sqrt{\frac{F_\mu}{F_S}} \sqrt{\frac{1/3}{f/8}} \left( d_p \frac{\rho_p}{\rho_f} \left( \frac{\rho_p - 1}{\rho_f} \right) \right)^{0.5} \times F_C
\]

- \( F_\mu \): Wall Fluid-Friction/Roughness Function
- \( F_S \): Shape Factor
- \( f \): Friction Coefficient
- \( d_p \): Particle Diameter
- \( \rho_p \): Particle Density
- \( \rho_f \): Fluid Density
- \( F_C \): Concentration Factor

\[
F_\mu = k \times (St)^n
\]

\[
St = \left( \frac{\rho_p d_p^2 V}{18 \mu f D} \right)
\]

\[
F_C = C^{0.1536} \times (1 - C)^{0.3564}
\]

**Liquid – Solid Flow**

<table>
<thead>
<tr>
<th></th>
<th>Saltation</th>
<th>Pickup</th>
<th>Scouring</th>
<th>Dispersed</th>
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<tbody>
<tr>
<td>( k )</td>
<td>7.1</td>
<td>7.2</td>
<td>9.2</td>
<td>10.3</td>
</tr>
</tbody>
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**Gas – Solid Flow**

<table>
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<th></th>
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<th>Incipient</th>
<th>Pickup</th>
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<tbody>
<tr>
<td>( k )</td>
<td>3.3</td>
<td>5.7</td>
<td>11.5</td>
</tr>
</tbody>
</table>

\[
V_{C,X} = V_C \times \cos \alpha
\]

\[
V_{S,X} = V_S \times \sin \alpha
\]

\[
V_T = V_{C,X} + V_{S,X}
\]

---

**Single-Phase Modeling Development**

Comparison with New Experimental Data – \( V_c \) vs PPM

Water-Sand Upward Flow; \( d_p = 300 \mu m - 75 \mu m \); Pipe Diameter = 50.8 mm, \( \Theta = 5^\circ \)
Single-Phase Modeling Development
Comparison with Experimental Data for Inclined Flow

Water-Sand Upward Flow; \( d_p = 300\mu m - 25\mu m \); Pipe Diameter = 101.6 and 50.8 mm, \( \theta = 5^\circ, 24^\circ \)

TUSMP Data  Cranfield Data — Perfect Agreement

![Graph showing predicted vs measured critical velocities with annotations]

- Coefficient of det. \((R^2) = 0.868\)
- Relative Error \((E_1) = 7.0\%\)
- Deviation Coefficient \((E_2) = -1.9\%\)

TUSMP Sand Transport Critical Velocity Predictor
Multi-phase Transport Module

START 

Read physical properties and \( V_{st} \)

\( \rightarrow \) Iterate on \( V_{sg} \)

\( \rightarrow \) Using a multiphase model \( \Rightarrow H_L \rightarrow D_h \)

\( \rightarrow \) Single phase flow model and \( D_h \rightarrow V_C \)

\( V_C = \frac{V_{st}}{H_L} \)

\( \rightarrow \) \( V_L = V_C \)

NO 

YES 

\( END \)

\( H_L \) (Liquid Holdup) \( \rightarrow H_{LL} \) (Liquid Level)

\[ D_h = \frac{4 A_W}{P_W} \]

\( A_W \): Wetted Area of the pipe

\( P_W \): Wetted Perimeter of the pipe

- Stratified Flow \( \Rightarrow \) Fan (2005) Model
- Intermittent Flow \( \Rightarrow \) Zhang (2003) Model
TUSMP Sand Transport Critical Velocity Predictor
Comparison with Experimental Data

I.D = 2”, $d_p = 300 \mu m$; C = 0.1% v/v, $\mu_L = 1$ cP

I.D = 4”, $d_p = 300 \mu m$; C = 0.1% v/v, $\mu_L = 1$ cP

Data from Najmi (2015)

TUSMP Sand Transport Critical Velocity Predictor
Comparison of Experimental Data with the Model Predictions

I.D = 2”, $d_p = 300 \mu m$; C = 0.1% v/v, $\mu_L = 1$ cP; Horizontal Flow

I.D = 4”, $d_p = 20 \mu m$; C = 0.1% v/v, $\mu_L = 1$ cP

Data from Najmi (2015)
TUSMP Sand Transport Critical Velocity Predictor
Comparison of Experimental Data with the Model Predictions

\[
\text{I.D} = 2\text{"}, \, d_p = 20 \mu m; \ C = 0.1\% \ v/v, \ \mu_L = 1 \text{cP}; \\
\text{Horizontal Flow}
\]

Data from Najmi (2015)

\[
\text{I.D} = 4\text{"}, \, d_p = 20 \mu m; \ C = 0.1\% \ v/v, \ \mu_L = 1 \text{cP}; \\
\text{Horizontal Flow}
\]

Data from Najmi (2015)

TUSMP Sand Transport Critical Velocity Predictor
Inclined Multi-phase Flows (New Data Example)

Comparison of the critical velocities between the calculated for horizontal flow and experimental results for inclined flows

\[
\text{I.D} = 2\text{-inch}, \ d_p = 300 \mu m; \text{ Sand Concentration} = 1000 \text{ ppm}; \ \Theta = 5^\circ \text{ upward flow}
\]

Data, \ \Theta = 5^\circ, \ 1000 \text{ ppm} — TUSMP Model (Horizontal)

Tulsa University Sand Management Projects
- Modified particle transport velocity: average liquid velocity for the entire slug unit

\[
V_{P,FILM} \rightarrow \overline{V}_p = \frac{V_{T,SLUG} \times L_{SLUG} + V_{FILM} \times L_{FILM}}{L_{SLUG} + L_{FILM}}
\]

- Modified hold up: average liquid holdup \((H_L)\) for the entire slug unit

\[
H_{L,FILM} \rightarrow \overline{H}_L = \frac{H_{L,SLUG} \times L_{SLUG} + H_{L,FILM} \times L_{FILM}}{L_{SLUG} + L_{FILM}}
\]
Model Enhancements

- Flow regimes and Unified graph – **Completed**
- Stratified flow:
  - Improved numerical solution of cubic equation – **Completed**
  - Modified closure relationship – **Completed**
- Modified model for slug flow – **Being tested**
- Inclination angle for single phase – **Being tested for small particles**
- Inclination angle for multiphase flow – **Being tested**
- Higher viscosities and gas densities – **Being tested**

Future Work

- Continue critical velocity database expansion:
  - Single-phase flow: proppant particles and effect of particle shape
  - Stratified-wavy multi-phase flow
- Critical sand concentration and velocity sub models:
  - Sand Bed Removal
- Sand transport in large pipe diameters (CFD Methodology)
- Uncertainty Estimation and Sensitivity Analysis of Sand Transport Models using Monte Carlo Simulation
End of Presentation

Thank you
Acoustic Sand Monitors
Experimental Studies

Asad Nadeem
PhD. Student, Mechanical Engineering

Tulsa University Sand Management Projects (TUSMP)
Mechanical Engineering Department
The University of Tulsa

November 11, 2021

Overview

- Introduction
  - ClampOn Sand Monitors
  - Roxar Sand Monitors
- Acoustic Sand Monitor Testing
  - Experimentation
  - Test Results
- Future Work
Introduction

- Acoustic sand monitors are used for sand alarm/detection procedures to limit the erosion of sand on pipelines.

- Acoustic monitors measure noise created by sand particles impacting the pipe wall. The flow also creates background noise that will interfere with determining the noise from sand impact.

- Monitor output depends on sand size, pipe size, fluid velocity, viscosity, density, and flow regime as well as other parameters.

Our goal is to provide the reliable raw data for several different flow conditions, monitor positions, loop orientations, and sand size.

Data is used to develop AI-TSR and mechanistic models for TSR.

This data, AI-TSR and Acoustic Programs may be used in the field for sand alert/detection operations.
ClampOn Sand Monitor, DSP-06 Model

ClampOn Sensor
ClampOn Mounted on Pipe
ClampOn System and Monitor

Roxar Sand Monitor, SAM 400 TC Model

Roxar Sensor
Roxar System
Sand Monitor Data Acquisition

- Software presents live feed of sand rate, velocity, and a “raw” value
  - Sand rate and velocity (based on user input/interface) values calculated internally by the software
  - “Raw” value is an unprocessed output directly from the acoustic monitor

- TUSMP analyzes “raw” value from monitor

Experimental Facility For Gas-Dominated Flow

- Loop schematic
Sensors Position after Bend 3-inch Elbow Test Section

ClampOn Sensor and Visible Section 3-inch Straight Pipe
Experimental Facility for Liquid-Dominated Flow (3 inch)

Loop schematic

- Test Section
- Sensor
- Filter
- Slurry Tank 300 gallons
- Pump

≈ 24 ft.
3"
4"

Erosion/Corrosion Research Center
Experimental Facility for Liquid-Dominated Flow (2-inch)

Loop schematic

2 Inch

4 Inch

Sensors

Experimental Facility for Liquid-Dominated Flow
2-inch Elbow Test Section

Sensors from other Vendor

Roxar

ClampOn
Acoustic Sand Monitor Testing

Threshold Sand Rate

- **Threshold Sand Rates (TSR)**
  - Minimum sand rate needed in order to detect sand using acoustic monitors
  - Sand flowing at a rate less than the threshold will pass through undetected
Determining Threshold Sand Rate

- Determination of Threshold Sand Rate

Graph showing the relationship between average monitor output and sand rate, with confidence intervals and thresholds.

Threshold Sand Rate Example

Graph showing raw values for a 4 inch pipe with 75 micron Clampon after bend in annular flow (Vsl=0.5 ft/sec, Vsg=65 ft/sec). The graph displays data for different sand concentrations, including no sand, 0.004%, 0.008%, 0.016%, 0.032%, 0.064%, and 0.128% sand concents. The graph includes markers for Clampon Elbow, Avg BG, BG + 2σ, and Average Raw Values.
**Threshold Sand Rate Example**

- **Threshold Sand Rate** -
  ClampOn, 90°, Vertical, Slurry Tank, 4-inches, 75 µm, Churn: (Vsl = 0.53 ft/s), (Vsg = 66.5 ft/s)

**Flow**

Average Monitor Output

0.00 0.01 0.10 1.00 10.00

0.0 0.01 0.1 1.0

- Background Noise
- 1σ
- 2σ
- Average Raw for Sand Conc.
- 68% Lower Bound CI
- 95% Lower Bound CI
- 99% Lower Bound CI
- 2σ Threshold Sand Rate
- 1σ Threshold Sand Rate
- 0σ Threshold Sand Rate
- Power (95% Lower Bound CI)
- Power (68% Lower Bound CI)
- Power (99% Lower Bound CI)

**Tulsa University Sand Management Projects**

**Progress Since Last ABM**

- **Spring ABM**
  - Experiments on Gas-Dominated 3 inch loop with 50 micron glass beads and 150 micron sand
  - Data Analysis
  - Experiments on Liquid-Dominated 2 inch loop with 600, 300, 75 and 25 micron sand

- **2021**
  - Size distribution analyses of 150 micron glass beads
  - Experiments on Liquid-Dominated Loop 3 inch with 50 micron
  - Experiments on Gas-Dominated 3 inch loop with 300 and 75 micron sand
  - TUSMP Modeling

Erosion/Corrosion Research Center
## Test Matrix (Gas-Dominated Flow)

<table>
<thead>
<tr>
<th>No.</th>
<th>Flow</th>
<th>Sand Size (Micron)</th>
<th>V_{SG} (ft/s)</th>
<th>V_{SL} (ft/s)</th>
<th>Pipe Diameter (Inches)</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gas-Dominated</td>
<td>300</td>
<td>29.5</td>
<td>1.7</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>68</td>
<td>0.31</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>98.7</td>
<td>0.32</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>98.7</td>
<td>1.7</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>162</td>
<td>0.17</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>162</td>
<td>1.2</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>160</td>
<td>0</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.03</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.03</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>29.5</td>
<td>1.7</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>68</td>
<td>0.31</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>98.7</td>
<td>0.32</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>100</td>
<td>0.4</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>100</td>
<td>0.4</td>
<td></td>
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<tr>
<td>15</td>
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<td></td>
<td>65</td>
<td>0.5</td>
<td></td>
<td>Vertical</td>
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<td>16</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.03</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.03</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.016</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.016</td>
<td></td>
<td>Vertical</td>
</tr>
</tbody>
</table>

## Test Matrix (Liquid-Dominated Flow)

<table>
<thead>
<tr>
<th>No.</th>
<th>Flow</th>
<th>Sand Size (Micron)</th>
<th>V_{SG} (ft/s)</th>
<th>V_{SL} (ft/s)</th>
<th>Pipe Diameter (Inches)</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Liquid-Dominated</td>
<td>50 (Glass beads)</td>
<td>0</td>
<td>11.48</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td>0</td>
<td>18.04</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>6.57</td>
<td>6.56</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td>8.53</td>
<td>18.37</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td>21.7</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>0</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td>6.57</td>
<td>6.56</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td>8.53</td>
<td>18.37</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td>21.7</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
<td>0</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>6.57</td>
<td>6.56</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td>8.53</td>
<td>18.37</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td>21.7</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
<td>0</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
<td>6.57</td>
<td>6.56</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td>8.53</td>
<td>18.37</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td></td>
<td>21.7</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td></td>
<td>0</td>
<td>21.65</td>
<td></td>
<td>Vertical</td>
</tr>
</tbody>
</table>
Liquid-Dominated Flow Experiment (3-inch)

Experimental Results
Liquid-Solid Flow, 3-inch Pipe, 150 µm Particles

Comparison between Sand and Glass beads
Vsl=18.04 ft/sec Vsg=0 ft/sec 3-inch

Mean Diameter for Glass Beads (micron) 154.6
Mean Diameter for Sand (micron) 232

Flow
- Glass-beads
- Sand
Experimental Results
Liquid-Solid Flow, 3-inch Pipe, 150 μm Glass Beads

- Threshold Sand Rate -
ClampOn, 90°, Vertical, Slurry Tank, 3-inches, 150 μm, 
Vsl = 18.04 ft/s, Vsg = 0.0 ft/s

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Experimental Results
Liquid-Solid Flow, 3-inch Pipe, 150 μm Sand

- Threshold Sand Rate -
ClampOn, 90°, Vertical, Slurry Tank, 3-inches, 150 μm, 
(Vsl = 18.04 ft/s), (Vsg = 0.0 ft/s)

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Experimental Conditions

\[ V_{sl} = 18.04 \text{ ft/s} \]
\[ V_{sg} = 0 \text{ ft/s} \]
Pipe Diameter = 3 inch
Sand Size = 50 micron (Glass beads)
Orientation: Vertical

Experimental Result
Liquid-Solid Flow, 3-inch Pipe, 50 µm Glass Beads
Experimental Result
Liquid-Solid Flow, 3-inch Pipe, 50 µm Glass Beads

- Threshold Sand Rate -
ClampOn, Vertical, Slurry Tank, 3-inches, 50 µm Glass-beads,
Liquid Only: Vsl = 18.04 ft/s, Vsg = 0 ft/s

<table>
<thead>
<tr>
<th>Slope</th>
<th>y-intercept</th>
<th>R²</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0σ</td>
<td>10150x + 645</td>
<td>0.9447</td>
<td>y = 10150x + 645</td>
</tr>
<tr>
<td>1σ</td>
<td>17455x + 1404</td>
<td>0.9394</td>
<td>y = 17455x + 1404</td>
</tr>
<tr>
<td>2σ</td>
<td>17392x + 1697</td>
<td>0.9394</td>
<td>y = 17392x + 1697</td>
</tr>
</tbody>
</table>

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Experimental Conditions

V_{SL} = 11.8 ft/s
V_{SG} = 0 ft/s
Pipe Diameter = 3 inch
Sand Size = 50 micron (Glass beads)
Orientation: Vertical

Tulsa University Sand Management Projects
Experimental Result
Liquid-Solid Flow, 3-inch Pipe, 50 μm Glass Beads

Clampon sensor (after bend)
Liquid Only $V_{sl}=11.8$ ft/sec $V_{sg}=0$ ft/sec
3-inches, 50 μm(Glass beads)

No Sand
0.004% Sand Conc.
0.008% Sand Conc.
0.016% Sand Conc.
0.032% Sand Conc.
0.064% Sand Conc.
0.128% Sand Conc.

Tulsa University Sand Management Projects
Gas-Dominated Flow Experiment (3-inch)

Experimental Conditions

\[ V_{SL} = 0.03 \text{ ft/s} \]
\[ V_{SG} = 100 \text{ ft/s} \]
Pipe Diameter= 3-inch
Sand Size= 50 micron (Glass beads)
Orientation: Horizontal
One Pass Experiment.
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Clampon sensor (after bend)
Annular (Vsl=0.03 ft/sec) (Vsg=100 ft/sec), 3-inches, 50µm(Glass Beads), Horizontal

Roxar Sensor (after bend)
Annular Vsl=0.03 ft/sec, Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Clampon sensor (Straight Pipe)
Annular, Vsl=0.03 ft/sec, Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal

Tulsa University Sand Management Projects

Comparison between Clampon and Roxar after Bend
Annular, Vsl=0.03 ft/sec, Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal

Tulsa University Sand Management Projects
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Comparison Clampon Straight and after bend sensors
Annular Vsl=0.03 ft/sec Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal

Extrapolated TSR (95%)
Value= 5.785 g/s
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Flow Pattern Video
$V_{SG} = 100 \text{ ft/s}, V_{SL} = 0.03 \text{ ft/s}, 50 \mu m$ Glass Beads, Horizontal Flow
Experimental Conditions

\( V_{SL} = 0.015 \, \text{ft/s} \)
\( V_{SG} = 100 \, \text{ft/s} \)
Pipe Diameter = 3 inch
Sand Size = 50 micron (Glass Beads)
Orientation: Horizontal
One Pass Experiment

Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Roxar Sensor (after bend)
Annular Vsl=0.015 ft/sec Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal

Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

Comparison between Clampon and Roxar after Bend
Annular Vsl=0.015 ft/sec Vsg=100 ft/sec, 3-inches, 50µm(Glass Beads), Horizontal
Experimental Results
Annular Flow, 3-inch Pipe, 50 µm Glass Beads

- Threshold Sand Rate -
  ClampOn, 90°, Horizontal, Slurry Tank, 3-inches, 50 µm(Glass Beads),
  Annular: Vsl = 0.015 ft/s, Vsg = 100 ft/s

Extrapolated TSR (95%) Value > 10 g/s

- Threshold Sand Rate -
  Roxar, 90°, Horizontal, Slurry Tank, 3-inches, 50 µm(Glass Beads),
  Annular: Vsl = 0.015 ft/s, Vsg = 100 ft/s

Extrapolated TSR (95%) Value not determined
Flow Pattern Video

$V_{SG} = 100 \text{ ft/s}, V_{SL} = 0.015 \text{ m/s}, 50 \mu \text{m Glass Beads}, \text{Horizontal Flow}$

Experimental Conditions

$V_{SL} = 2.1 \text{ ft/s}$
$V_{SG} = 29.5 \text{ ft/s}$
Pipe Diameter: 3-inch
Sand Size: 75 micron
Orientation: Horizontal
Experimental Results
Slug Flow, 3-inch Pipe, 75 µm Sand

Comparison between Clampon and Roxar after Bend
Slug Vsl=2.1 ft/s Vsg=29.5 ft/s, 3-inches, 75µm, Horizontal

Raw Values

01:12:00 PM 01:26:24 PM 01:40:48 PM 01:55:12 PM 02:09:36 PM 02:24:00 PM 02:38:24 PM

Time

Tulsa University Sand Management Projects

Experimental Results
Slug Flow, 3-inch Pipe, 75 µm Sand

Roxar Sensor (after bend)
Slug Vsl=2.1 ft/s Vsg=29.5 ft/s, 3-inches, 75µm, Horizontal

Raw Values

01:12:00 PM 01:26:24 PM 01:40:48 PM 01:55:12 PM 02:09:36 PM 02:24:00 PM 02:38:24 PM

Time

Tulsa University Sand Management Projects
Liquid-Dominated Flow Experiment (2-inch)

Experimental Conditions

\[ V_{SL} = 6.5 \, \text{ft/s} \]
\[ V_{SG} = 6.5 \, \text{ft/s} \]
Pipe Diameter = 2 inch
Sand Size = 300 micron
Orientation: Vertical
Experimental Result
Slug Flow, 2-inch Pipe, 300 µm Sand

Clampon sensor (after bend)
Vsl=6.5 ft/s Vsg=6.5 ft/s, 2-inches, 300µm, Vertical

Roxar Sensor (after bend)
Vsl=6.5 ft/s Vsg=6.5 ft/s, 2-inches, 300µm, Vertical
Experimental Result
Slug Flow, 2-inch Pipe, 300 µm Sand

Comparison between Clampton and Roxar after Bend
(Vsl=6.5 ft/s, Vsg=6.5 ft/s, 2-inches, 300µm, Vertical)

- Threshold Sand Rate -
ClampOn, 90°, Vertical, Slurry Tank, 2-inches, 300 µm,
Vsl = 6.5 ft/s, Vsg = 6.5 ft/s
Experimental Result
Slug Flow, 2-inch Pipe, 300 µm Sand

Flow Pattern Video
$V_{SG} = 6.5 \text{ ft/s}, V_{SL} = 6.5 \text{ ft/s}, 300 \mu m \text{ Sand, Vertical Flow}$
### Summary (Gas-Dominated Flow)

#### Test Results

<table>
<thead>
<tr>
<th>Flow</th>
<th>Flow Regime</th>
<th>Sand Size</th>
<th>V&lt;sub&gt;SG&lt;/sub&gt;</th>
<th>V&lt;sub&gt;SL&lt;/sub&gt;</th>
<th>Pipe Diameter</th>
<th>Orientation</th>
<th>TSR ClampOn (g/s)</th>
<th>95%</th>
<th>68%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
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<td>Annular Flow</td>
<td>50 (Glass Beads)</td>
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<td>0.4</td>
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### Summary (Liquid-Dominated Flow)

#### Test Results

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<th>Flow</th>
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<th>V&lt;sub&gt;SG&lt;/sub&gt;</th>
<th>V&lt;sub&gt;SL&lt;/sub&gt;</th>
<th>Pipe Diameter</th>
<th>Orientation</th>
<th>TSR ClampOn (g/s)</th>
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<th>0%</th>
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### Experiment Results Comparison

<table>
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<tr>
<th>Author Name</th>
<th>( V_{SL} ) (ft/s)</th>
<th>( V_{SG} ) (ft/s)</th>
<th>Orientation</th>
<th>Sand Size (μm)</th>
<th>TSR (95%)</th>
<th>TSR (68%)</th>
<th>TSR (0%)</th>
<th>B.G Noise</th>
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<tr>
<td>Jorge (2013)</td>
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<td>Asad (2021)</td>
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<td>0.569</td>
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</table>

### Future Research

- Run experiments with annular/mist flow conditions in 3 inch pipe diameter with 50 micron glass beads.
- Run experiments with liquid-dominated flow conditions in 2 and 3 inch pipe diameter.
- Calculate the anticipated TSR value for those experiments in which we couldn’t obtain.
- Work on TUSMP Model to obtain theoretical expression to get TSR values and compare with experimental TSR values.
- Continue working on previous data sets to add to the artificial intelligence model.
- Rerun those experiments in which threshold sand rates were not determined.
- Continue making and analyzing flow pattern videos.
# Future Test Matrix

<table>
<thead>
<tr>
<th>No.</th>
<th>Flow</th>
<th>Sand Size</th>
<th>$V_{SG}$</th>
<th>$V_{SL}$</th>
<th>Pipe Diameter</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>50 (Glass beads)</td>
<td>98.5</td>
<td>0.15</td>
<td>3</td>
<td>Horizontal</td>
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<tr>
<td>2</td>
<td></td>
<td></td>
<td>98.5</td>
<td>0.15</td>
<td>Vertical</td>
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</tr>
<tr>
<td>3</td>
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<td>1.00</td>
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<td>98.5</td>
<td>0.016</td>
<td>Vertical</td>
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</table>

Thank You!

Questions
AI for Acoustic Monitoring – Prediction of Threshold Sand Rates

Jamie (Yijie) Li

Ph.D. Student in Computer Science

Tulsa University Sand Management Projects
Mechanical Engineering Department
The University of Tulsa

November 11, 2021

Outline of Presentation

- Introduction/Objectives
- Background/Previous Work
- Timeline/Progress to Date
- Results/Implementation
- Summary
Introduction/Objectives

- Problem Statement:
  - Acoustic sand monitors are non-intrusive devices and can be used to provide a warning when sand is being produced in pipelines and determine the sand rates, but it’s hard to simulate the dynamics via physical models. E/CRC already developed machine learning models to predict Threshold Sand Rates using pure data-driven models.
  - E/CRC has obtained new experimental data. It is possible to utilize pure data-driven models that may eliminate the potential negative effects from possible mechanistic model assumptions.

- Objective:
  - Use machine learning methods to predict TSR .95, TSR .68 and TSR 0.
  - Develop a VBA program utilizing data-driven models to predict TSR.

Background

- Machine learning extracts hidden pattern in the data and makes prediction for unseen circumstances.
  - Elastic Net (ENET), Random Forest (RF), Support Vector Machine (SVM), and eXtreme Gradient Boosting (XGBoost) were selected to build data-driven models.
    - ENET: Linear regression model with regularization.
    - SVM: Non-linear instance-based method.
Timeline

- **ABM meeting (May 2021):**
  - 237 cases of experimental results are included in the database.
  - Input variables: Pipe diameter, particle size, inclination, superficial liquid/gas velocity, mixture density/viscosity, flow regime, and mean/standard deviation of background noise level.

- **Update (Nov 2021):**
  - 298 cases of experimental results are included in the database.
  - Input variables: Pipe diameter, particle size, inclination, superficial liquid/gas velocity, mixture density/viscosity, flow regime, background noise, x2.sigma (the standard deviation of bkg).
  - New flow patterns, “Stratified Flow”, “Gas-Only” and “Liquid-Only” were added in TSR database.

---

**Distribution of TSRs**

Corr: 0.881***  Corr: 0.371***  Corr: 0.977***  Corr: 0.868***  Corr: 0.558***  Corr: 0.930***
### Results (95% Confidence Interval)

<table>
<thead>
<tr>
<th></th>
<th>ENET</th>
<th>RF</th>
<th>SVM</th>
<th>XGBTREE</th>
</tr>
</thead>
<tbody>
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<td><strong>With BKG and sigma</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>R square (New)</td>
<td>0.6415</td>
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### Results (68% Confidence Interval)

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Threshold Ratio: Prediction/observation

1/Threshold Ratio line; 
\[
\frac{\text{Prediction}}{\text{observation}} = \frac{1}{\text{threshold ratio}}
\]

Model

Data point; e.g., 196 refers to the case on Row 197 in the database

Prefect match line (prediction=observation)

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Results (Interface)

Step 1:

Step 2:

Step 3:

Summary

- We added more cases to the database and added background noise and x2.sigma for training the models.
- New flow patterns, “Stratified Flow”, “Gas-Only” and “Liquid-Only” were added in TSR database
- We added extreme Gradient Boosting model.
- The results of extreme Gradient Boosting show high $R^2$ values for most of TSR levels.
- Add more case to current database in the future.
Thank You For Your Attention!
TUSMP Acoustic Sand Monitors Modeling

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The University of Tulsa

November 11, 2021

Overview

- Introduction
- Acoustic Program
- Acoustic Model Equation for Monitor Output with respect to Sand Rate
- TSR Prediction
- Observations
- Future Development
Acoustic Program – Background

- Acoustic Program was developed using data and experimentation from a 2-inch and 1-inch flow loops.
- The program was developed for two models:
  - A flow regime independent model if the flow regime is unknown, or
  - A flow regime dependent model including annular, slug, bubble, mist, churn and the option to calculate the flow regime

Acoustic Program - Calibration

- Acoustic Program was originally developed to allow users to calibrate their sensors given that they know the fluid conditions, sand rate, monitor output, and background noise
- Calibration should be performed at the nominal fluid conditions of the system
Acoustic Program

- Acoustic Program operates in two ways:
  - User inputs the properties of the well, or the flow conditions and sand rate. The program then outputs the calibration factor for the given condition.
  - User inputs the properties of the well, or the flow conditions and the calibration factor. The program then outputs the sand rate for the given condition.

Acoustic Program – Calibration Factor

- Developed to relate raw monitor output to sand rate

\[ V_{rms}^2 - V_b^2 = S \left( C_i m_p U_i \right) \left( C_i m_p U_i + 2V_b \right) \]

Where:
- \( V_{rms} \) = Raw monitor output signal
- \( V_b \) = Background noise
- \( S \) = Sand Rate
- \( C_i \) = Calibration Factor
- \( m_p \) = Mass of the sand particle
- \( U_i \) = Characteristic impact velocity of the particle

- Acoustic program uses same models as SPPS to determine representative particle impacts \( U_i \)
Comparison of Predicted And Experimental Sand Rates

Acoustic Program – Annular, 3-inch, 150 µm Sand, Vertical

\[ V_{SL} = 0.5 \text{ ft/s}, \ V_{SG} = 100 \text{ ft/s} \]

<table>
<thead>
<tr>
<th>Average Difference b/w Predicted &amp; Actual Sand Rates</th>
<th>0.006 g/s</th>
</tr>
</thead>
</table>

- Predicted Sand Rates
- Experimental Sand Rates

Prediction of TSR Using Calculated Sand Rates

Acoustic Program – Annular, 3-inch, 150 µm Sand

\[ V_{SL} = 0.5 \text{ ft/s}, \ V_{SG} = 100 \text{ ft/s}, \text{ Vertical} \]

<table>
<thead>
<tr>
<th>Predicted TSR</th>
<th>Experimental TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 g/s</td>
<td>0.03 g/s</td>
</tr>
</tbody>
</table>

- Predicted Sand Rate
- Background Noise Plus 2 Sigma
- 2σ Threshold Sand Rate = 0.02 g/s
Comparison of Predicated And Experimental Sand Rates

Acoustic Program – Annular, 3-inch, 150 µm Sand, Vertical

Vsl=0.31 ft/s, Vsg=98.6 ft/s

Average Difference b/w Predicted & Actual Sand Rates

0.05 g/s

Predicted Sand Rates

Experimental Sand Rates

No Sand

Prediction of TSR Using Calculated Sand Rates

Acoustic Program – Annular, 3-inch, 150 µm Sand

Vsl = 98.6 ft/s, Vsg = 0.31 ft/s, Vertical

TSR Predicted Value

Predicted TSR
Experimental TSR

0.01 g/s
0.02 g/s

2σ Threshold Sand Rate = 0.01 g/s

Background Noise Plus 2 Sigma
Comparison of Predicated And Experimental Sand Rates

Acoustic Program – Liquid-Solid Flow, 3-inch, 50 µm Glass Beads, Vertical

$V_{SL} = 18.04 \text{ ft/s}, V_{SG} = 0 \text{ ft/s}$

**Average Difference b/w Predicted & Actual Sand Rates** 1.7 g/s

**Predicted Sand Rates**

**Experimental Sand Rates**

Prediction of TSR Using Calculated Sand Rates

Acoustic Program – Liquid-Solid Flow, 3-inch, 50 µm Glass Beads

$V_{SL} = 18.04 \text{ ft/s}, V_{SG} = 0 \text{ ft/s}$, Vertical

**TSR Predicted Value**

- Predicted TSR: 1.20 g/s
- Experimental TSR: 1.73 g/s

$2\sigma$ Threshold Sand Rate = 1.20 g/s

Background Noise Plus 2
Observations

- Maximum 30% error is observed in prediction TSR values using predicted Sand rates and Background Noise plus 2 Sigma Values.

- In other cases error was observed as low as 3% of the actual TSR Values.

Acoustic Program – Importance of Calibration Factor

\[ V_{ms}^2 - V_b^2 = S \left( C_l m_p U_i \right) \left( C_l m_p U_i + 2V_b \right) \]

Where:
- \( V_{ms} \) = Raw monitor output signal
- \( V_b \) = Background noise
- \( S \) = Sand Rate
- \( C_l \) = Calibration Factor
- \( m_p \) = Mass of the sand particle
- \( U_i \) = Characteristic impact velocity of the particle

For Liquid:
\[ C = 1.23 \times 10^6 \left( Re_{SL} \right)^{1.27} \]

For Bubble:
\[ C = 2.32 \times 10^8 \left( Re_{SG} \right)^{0.865} \left( Re_{SL} \right)^{0.179} \]

For Dispersed Bubble:
\[ C = 1.0 \times 10^8 \left( Re_{SG} \right)^{0.374} \left( Re_{SL} \right)^{-0.262} \]

For Slug/Churn:
\[ C = 2.01 \times 10^3 \left( Re_{SG} \right)^{1.20} \left( Re_{SL} \right)^{0.931} \]

For Annular:
\[ C = 3.8 \times 10^9 \left( Re_{SG} \right)^{-0.972} \]

For Gas/Very Low Liquid-High Gas:
\[ C = 4.95 \times 10^7 \left( Re_{SG} \right)^{0.864} \]

\[ Re_{SG} = \frac{d_p V_{SG} \rho_G}{\mu_G} \]

\[ Re_{SL} = \frac{d_p V_{SL} \rho_L}{\mu_L} \]
Future Development

➢ Develop a model to predict TSR values by utilizing the data of TUSMP Experiments for different pipe diameters (1-inch to 4-inch), different flow regimes and different sand sizes.
➢ Develop correlations for C values based on all experimental values.

Thank You!

Questions
Sand Transport – AI Developments and Software Updates

Ronald E. Vieira

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November 11, 2021

Outline

- Introduction
- Objectives and Approach
- AI-ML Methodology
- Current Developments
  - Database Expansion
  - New ML Algorithm and Evaluations
  - Use of Dimensionless Variables
  - Machine Learning Approach for Multi-phase Flows
- Future Work
Introduction

Critical Velocity Prediction

- The evident practical significance of the critical velocity has motivated many studies at determining it experimentally to permit its prediction under more extended conditions
- This accumulation of experimental data makes also possible the application of data-driven methods for characterizing liquid-solid flows for a broader range of conditions
- While there is a vast literature on solids transport modeling in pipelines, less effort is devoted to the application of Machine Learning (ML) algorithms in the prediction of critical velocities

Objective

- The purpose of this work is to investigate the use of several machine learning algorithms to predict the critical velocities of single-phase and multiphase carrier fluids in horizontal and inclined flow conditions
- Develop a tool to predict critical velocities in pipes via machine learning, using accessible parameters as inputs, namely, fluid and particle properties and inclination angles
Two ML algorithms are trained large datasets (more than 1600 data points) of critical velocities in single-phase carrier fluid that is collected from open source: articles and dissertations

The trained algorithms are:
- Linear Regression,
- Random Forest

The input variables are:
- Sand volumetric concentration
- Pipe diameter
- Fluid density
- Fluid viscosity
- Particle density
- Particle diameter.
**Machine Learning Prediction Module**  
Liquid-Sand and Gas-Flow

<table>
<thead>
<tr>
<th></th>
<th>Loop 1</th>
<th>Loop 2</th>
<th>Loop 3</th>
<th>Loop 4</th>
<th>Loop 5</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LM</strong></td>
<td>Test</td>
<td>0.847</td>
<td>0.846</td>
<td>0.857</td>
<td>0.848</td>
<td>0.846</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.846</td>
<td>0.854</td>
<td>0.822</td>
<td>0.843</td>
<td>0.858</td>
</tr>
<tr>
<td><strong>RF</strong></td>
<td>Test</td>
<td>0.984</td>
<td>0.981</td>
<td>0.984</td>
<td>0.981</td>
<td>0.981</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>0.963</td>
<td>0.958</td>
<td>0.93</td>
<td>0.966</td>
<td>0.974</td>
</tr>
</tbody>
</table>

LM = Linear Regression  
RF = Random Forest


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**Machine Learning Prediction Module**  
**Current Developments**

- Expanded database of critical velocity  
  - From 1648 to 2023 data points  
- Include pipe inclination as input variable  
- Implementation of New ML Algorithms  
  - Extreme Gradient Boosting (XGB)  
- Evaluation of new data pre-processing  
  - Use of dimensionless numbers  
- Machine Learning Approach for Multi-phase Flows

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Machine Learning Prediction Module
Particle Transport Database

- Single-Phase Flow
- 2023 data points
  - 1486 solid-liquid
  - 537 gas-solid
- 55 Authors

Machine Learning Prediction Module
Methodology

(a) Data acquisition and organization (experiment list)
Input: flow parameters                      Output parameter
• Volumetric sand concentration
• Particle Density
• Pipe inclination
• Particle diameter
• Fluid density
• Pipe hydraulic diameter
• Fluid viscosity
• Critical velocity

(b) Data preprocessing
• Detection of abnormal values
• Correlation analysis

(c) Training and testing ML Models
• Elastic Net (ENET)
  - Support Vector Machine (SVM)
  - Extreme Gradient Boosting (XGB)
• Random Forest (RF)

(d) Comparison and performance of ML Models
• Sand concentration
• Fluid Viscosity
• Pipe inclination
• Sand Size

### Machine Learning Prediction Module

**Expanded Database, Inclination and XGB Algorithm**

#### R² values

<table>
<thead>
<tr>
<th></th>
<th>Loop 1</th>
<th>Loop 2</th>
<th>Loop 3</th>
<th>Loop 4</th>
<th>Loop 5</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>XGB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validation</td>
<td>0.920</td>
<td>0.910</td>
<td>0.908</td>
<td>0.902</td>
<td>0.919</td>
<td>0.907</td>
</tr>
<tr>
<td>Test</td>
<td>0.779</td>
<td>0.919</td>
<td>0.897</td>
<td>0.931</td>
<td>0.895</td>
<td>0.901</td>
</tr>
<tr>
<td>RF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validation</td>
<td>0.921</td>
<td>0.896</td>
<td>0.898</td>
<td>0.896</td>
<td>0.905</td>
<td>0.900</td>
</tr>
<tr>
<td>Test</td>
<td>0.900</td>
<td>0.924</td>
<td>0.902</td>
<td>0.939</td>
<td>0.916</td>
<td>0.903</td>
</tr>
</tbody>
</table>

#### Validation Performance

![Graph showing predicted vs. observed critical velocity](attachment:image1.png)

- **XGB**
  - R² = 0.900
  - R² = 0.907

- **RF**
  - R² = 0.900
  - R² = 0.907

---

### Machine Learning Prediction Module

**Overall Performance of ML for Liquid-Sand and Gas-Liquid Flows**

![Graph showing predicted vs. observed critical velocity](attachment:image2.png)

- **XGB**
  - R² = 0.952
  - R² = 0.969

- **RF**
  - R² = 0.928
  - R² = 0.989

#### Statistic Parameters

- Coefficient of determination, R²
- Relative error, E₁
- Deviation coefficient, E₂

<table>
<thead>
<tr>
<th>Model</th>
<th>Medium</th>
<th>E₁ (%)</th>
<th>E₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XGB</td>
<td>Gas-Sand</td>
<td>4.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Liquid-Sand</td>
<td>5.5</td>
<td>4.5</td>
</tr>
<tr>
<td>RF</td>
<td>Gas-Sand</td>
<td>5.9</td>
<td>-2.1</td>
</tr>
<tr>
<td></td>
<td>Liquid-Sand</td>
<td>2.9</td>
<td>-1.2</td>
</tr>
</tbody>
</table>
Machine Learning Prediction Module
Performance of AI-ML Models for Liquid-Sand Flow

**Dependence of critical velocity on sand concentration**

\[ MAE = \frac{1}{N} \sum_{i=1}^{N} |x_{pred,i} - x_{data,i}| \]

Data from Cranfield University (2010)

**Dependence of critical velocity on pipe inclination**

Data from Roco (1977)

**Dependence of critical velocity on sand size**

\( d_p = 20 \text{ to } 300 \mu m \)

Data from Hill (2011)
Machine Learning Prediction Module
Method 2: Use of Dimensionless Variables

- For creating the predictive models applicable for different types of liquids and gases and for reducing the number of input features when training ML algorithms, the following set of dimensionless variables are chosen:

  Particle Reynolds Number: \( N_{Re} = \frac{D p L \left( g D \left( \frac{\rho_s}{\rho_L} - 1 \right) \right)^{0.5}}{\mu_L} \)

  Density Ratio: \( N_R = \frac{\rho_s - \rho_L}{\rho_L} \)

  Diameter Ratio: \( N_D = \frac{d_p}{D} \)

  where \( \left( g D \left( \frac{\rho_s}{\rho_L} - 1 \right) \right)^{0.5} \) is the reference ‘velocity’ proposed by Turian (1980)

- Once the above dimensionless numbers were calculated, pipe inclination angles from horizontal (PA), sand (or particle) concentrations (SC), and critical velocity \( (V_C) \) were included as final input features for training and testing the ML algorithms.

<table>
<thead>
<tr>
<th>Model</th>
<th>XGB</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas-Sand</td>
<td>0.909</td>
<td>0.874</td>
</tr>
<tr>
<td>Liquid-Sand</td>
<td>0.939</td>
<td>0.974</td>
</tr>
</tbody>
</table>
Machine Learning Prediction Module
Approach for Multi-phase Flows

- ML is used to predict the Critical Superficial Liquid Velocity at a given superficial gas velocity.
- More than **2000 data points** are used for training and validation:
  - Angelsen (1989)
  - Ibarra (TU, 2012)
  - Hill (TUSMP, 2011)
  - Najmi (TUSMP, 2014)
  - Sajeev (TUSMP, 2019)
  - Darbian (TU, 2018)
  - Fajemiduje (2019)
  - Cranfield University

- Random Forest and Extreme Gradient Boosting Algorithms are used

Read physical properties: $SC, PA, D, d, \mu, \rho, \rho_L, \rho_G, ST$

Using a given $V_{SG}$, calculate dimensionless numbers $-> Re_{SG}, Fr_{SG}$. Plus $d/D, \rho/G, \rho_L, \mu_L$

$Re_{SG} = \frac{\rho_G * V_{SG} * D}{\mu_G}$

$Fr_{SG} = \frac{\rho_G}{(\rho_L - \rho_G) g * D * \cos \theta}$

$DR = \frac{d}{D}$  

$RR = \frac{\rho_G}{\rho_L}$  

Liq. Viscosity: $\mu_L$

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<table>
<thead>
<tr>
<th>Model</th>
<th>Testing Set RSME (m/s)</th>
<th>$R^2$</th>
<th>Training Set RSME (m/s)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>0.033</td>
<td>0.948</td>
<td>0.015</td>
<td>0.988</td>
</tr>
<tr>
<td>XGB</td>
<td>0.026</td>
<td>0.966</td>
<td>0.004</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Tulsa University Sand Management Projects
Machine Learning Prediction Module
Approach for Multi-phase Flows

**Horizontal Flow**

- **I.D = 2**, \(d_p = 300 \, \mu m\); \(C = 0.1\% \, v/v\), \(\mu_L = 1 \, cP\)
- **I.D = 4**, \(d_p = 300 \, \mu m\); \(C = 0.1\% \, v/v\), \(\mu_L = 1 \, cP\)

Data from Najmi (2015)

Machine Learning Prediction Module
Hybrid Approach for Multi-phase Flows

\[H_L (Liquid \ Holdup) \rightarrow H_{LL} (Liquid \ Level)\]

\[D_h = \frac{4 \, A_W}{P_W}\]

- **Current Mechanistic Models:**
  - Stratified Flow- Fan (2005) Model

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Future Work

➢ Continue tuning and improvement of evaluation scores of current models
➢ Release new version
➢ Explore Deep Learning techniques
➢ AI Model for Multiphase Flow
  ➢ Extend the single-phase flow model to Multiphase Flow

End of Presentation

Thank you