DEM Model of Clogging in Millimeter Scale Channels in Drip Irrigation Emitters

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Commercial NPC Inline Emitter

- Labyrinth channel
- Inlets
- Flow through pipe
- Flow into inlets

Massachusetts Institute of Technology
**DEM Model Validation: Bulk Flow**

**Study Parameters**
- Total Inlet Pressure: 50,000 Pa
- Outlet Pressure: 0 Pa
- Standard k-ε turbulence


[2] Realizable k- ε two layer
DEM Model Overview

- Bulk Flow: 2\textsuperscript{nd} order implicit unsteady solver; 2\textsuperscript{nd} order convection, segregated (SIMPLE) P-V coupling

- Turbulence: Realizable k-\varepsilon turbulence with two-layer all y+ wall treatment

- Particles: Lagrangian multiphase DEM spherical particles; pressure gradient and drag forces; two-way coupling

- Hertz Mindlin no-slip contact model with frictional coefficients as defined in [1]

Solid and water properties as defined in [1]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Density distribution</td>
<td>\rho</td>
<td>kg/m\textsuperscript{3}</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>Particle diameter</td>
<td>d</td>
<td>\mu m</td>
<td>65 \mu m, 100 \mu m, 150 \mu m</td>
</tr>
<tr>
<td></td>
<td>Rolling friction coefficient</td>
<td>\mu_r</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Sliding friction coefficient</td>
<td>\mu_s</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Poisson's ratio</td>
<td>\nu</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Young's modulus</td>
<td>E</td>
<td>N/m\textsuperscript{2}</td>
<td>2 \times 10\textsuperscript{7}</td>
</tr>
<tr>
<td></td>
<td>Coefficient of restitution</td>
<td>C</td>
<td></td>
<td>0.545</td>
</tr>
<tr>
<td></td>
<td>Particle velocity at inlet</td>
<td>V</td>
<td>m/s</td>
<td>1.02</td>
</tr>
<tr>
<td>Water</td>
<td>Density</td>
<td>\rho</td>
<td>kg/m\textsuperscript{3}</td>
<td>996.2</td>
</tr>
<tr>
<td></td>
<td>Viscosity</td>
<td>\mu</td>
<td>kg/m\textsuperscript{3}/s</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Velocity at inlet</td>
<td>V</td>
<td>m/s</td>
<td>1.02</td>
</tr>
</tbody>
</table>
DEM Model Validation: Particle Tracks

- Study ran simulation for a time of 1s with a time step of 0.001s [1]; due to computational limitations, a time step of 0.02s was used.
- Particle flow rate selected as 100 particles/sec.

Particle trajectories [1]

50 µm

100 µm

150 µm
DEM Model Validation: Particle Tracks

- Simulated trend matches trend from study [1] and other publications [2]
  - Would expect a longer residence time because recirculating particle tracks were not removed from average
  - Relatively small number of simulated particles may skew absolute values

<table>
<thead>
<tr>
<th>Particle Diameter (µm)</th>
<th>Average Residence Time (s)</th>
<th>Average Residence Time of Particles not in Recirculation (s) [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>0.0173</td>
<td>0.019</td>
</tr>
<tr>
<td>100</td>
<td>0.0322</td>
<td>0.024</td>
</tr>
<tr>
<td>150</td>
<td>0.115</td>
<td>0.044</td>
</tr>
</tbody>
</table>
Model Validation: Steady State Results (One Phase) for Tested Emitters

*Flow is modeled as turbulent in published literature ([1], [2], [3]); Realizable k-ε selected for robustness after extensive comparison*
Model Validation: Steady State Results (One Phase) for Tested Emitters

- For computational efficiency, simulated domain did not include filter or pipe flow (added resistance)
  - Simulation trends match expectations
- Mesh used curvature refinement and volume transition limiters and could not be refined evenly to calculate order of convergence
- Relative error between grids: ~0.01 m/s

3D Segregated flow (SIMPLE) solver with 2nd order convection, RANS realizable k-ε* two layer with all y+ treatment and wall y+ <1

*Flow is modeled as turbulent in published literature ([1], [2], [3]); Realizable k-ε selected for robustness
DEM Model Results

Particle tracks in 1.6 L/hr emitter

Velocity field in 1.6 L/hr emitter
Comparing Clogging in Emitters with Different Flow Rates

- Defined dimensionless time to compare data between emitters of different flow rates

\[ t_{\text{char}} = \left( \frac{L_{\text{characteristic}}}{v_{\text{outlet}}} \right) \]

\[ t^* = \left( \frac{t_{\text{avg sand residence time}}}{t_{\text{char}}} \right) \]

Characteristic length
Comparing Clogging in Emitters with Different Flow Rates

- Trends appears correlated to flow rate; pressure variations in experiment may have skewed data
  - Additional simulation and experimental data necessary to evaluate numerical confidence and draw conclusive trends
  - Future work: How does the simulated particle concentration affect results?

Experiments used 180 µm aluminum grit
Flow Field and Clogging Behavior

Velocity filtered into bulk velocity and velocity in recirculation areas

Lower flow rates in the recirculation region may correspond to improved clogging resistance
Design Applications

(1) Path design of traditional labyrinth channels using $S_r$ as a design factor to minimize

- Simulation requires 10 minutes, while DEM simulation requires 6 hours

- Published studies in literature on optimizing design focus on DEM and experimental studies, [7]

(2) Novel path designs that avoid low flow velocity regions
Design Applications

(1) Path design of traditional labyrinth channels using $S_r$ as a design factor to minimize

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(2) Novel path designs that avoid low flow velocity regions

Design: Flow Path Around Cylinders

No large zones with low flow velocity
Design: Flow Path Around Cylinders

- The cylinder flow path has a significantly lower average residence time for particles than the traditional design, even at a lower flow rate.

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Outlet Velocity (m/s)</th>
<th>Average Residence Time (s)</th>
<th>Length Scale (m)</th>
<th>Characteristic Time (s)</th>
<th>t*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo</td>
<td>0.649</td>
<td>0.0836</td>
<td>0.023</td>
<td>0.035</td>
<td>2.402</td>
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<tr>
<td>Excel</td>
<td>0.54</td>
<td>0.02139</td>
<td>0.021</td>
<td>0.039</td>
<td>0.545</td>
</tr>
<tr>
<td>Cylinders</td>
<td>0.54</td>
<td>0.02139</td>
<td>0.021</td>
<td>0.039</td>
<td>0.545</td>
</tr>
</tbody>
</table>

![Graph showing flow rate vs. pressure for Turbo Excel and Cylinders](image)
References


NPC Emitter Model with Filter and Pipe [3]

Clogging Experimental Set-Up Overview

Clogging Experimental Design & Data Collection: Trang Luu

- Clogging tests use different recommended times for operation and data collection and intermission (particle settling)
  - Cemagref: 8 hours operation, 16 hours intermission [5]
  - Niu, et. al.: 30 minutes operation, 6 hours intermission [6]
- Selected time for experiments: 30 minute operation, 30 minutes intermission
- During intermission, the concentration of 180 µm was increased