COMPUTATIONAL FLUID DYNAMICS MODELING OF HIGH LEVEL WASTE PLUG FORMATION

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OBJECTIVE

- Develop a computational model of fluid flow in a pipe to provide analysis of pipe plugging which has been reported during transfer operations at DOE sites.
- The model uses a multi-physics simulation software, COMSOL, to simulate and predict the plug formation process in a high-level waste pipeline in a stepwise approach.
- The objective is to provide better understanding of the interactions between critical flow velocity, chemical reaction with formation of solids, and solids settling, and ultimately plug formation.
- Initial simulations were conducted for fluid flow, chemical reactions and solids settling using a 2D multiphase simulations.
- The work will be used to provide analysis of the environmental factors causing plug formation.

NUMERICAL APPROACH

Flow Modeling

Mass Equation

$$\boxed{\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0}$$

Momentum Equation

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial p}{\partial x} + \mu\nabla^2 u + F_x$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \frac{\partial p}{\partial y} + \mu\nabla^2 v + F_y$$

Chemical Reaction Modeling

$$\boxed{\frac{\partial c}{\partial t} - \nabla\cdot(D\nabla c) + \mathbf{u}\cdot\nabla c = R}$$

Two Phase Modeling

Mass Equation

$$\boxed{(\rho_c - \rho_d)\left[\nabla\cdot(1-c_d)\mathbf{u}_{slip} - D_{md}\nabla\phi_d) + \frac{m_{dc}}{\rho_d}\right] + \rho_c(\nabla\cdot\mathbf{u}) = 0}$$

Momentum Equation

$$\rho u_t + \rho(u\cdot\nabla)u = -\nabla p - \nabla\cdot\tau_{Gm} + \rho g + F$$

$$-\nabla\cdot\left[\rho c_d(1-c_d)\left(u_{slip} - \frac{D_{md}}{(1-c_d)\phi_d}\nabla\phi_d\right)\left(u_{slip} - \frac{D_{md}}{(1-c_d)\phi_d}\nabla\phi_d\right)\right]$$

CFD Modeling
↓
Flow Modeling
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Chemical Reaction Modeling
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Two Phase Modeling
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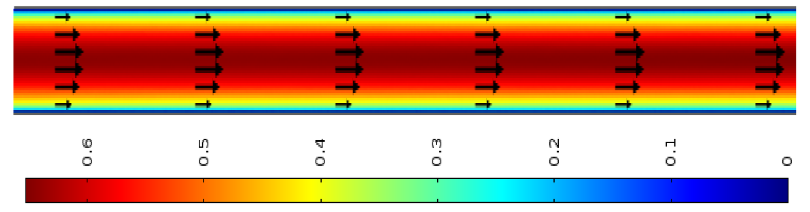
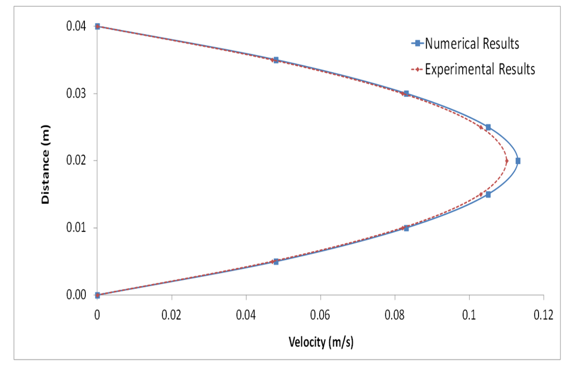
3D Analysis

RESULTS

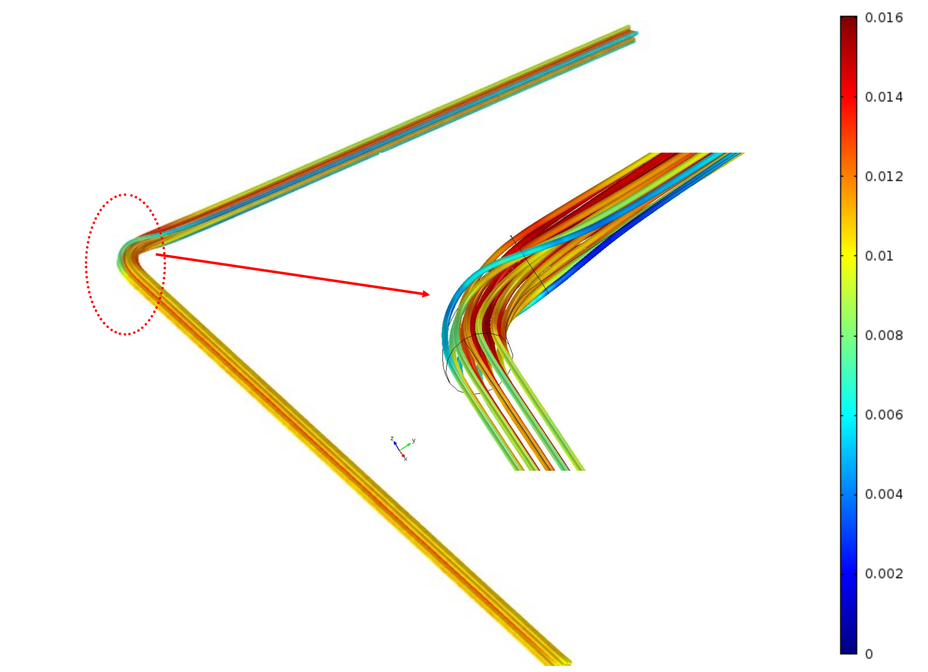
STEADY STATE FLOW MODELING



The figure above shows that velocity is greatest in the center and goes to zero at the walls of the pipe. The black arrows represent the parabolic profile as the flow travels along the pipe length.

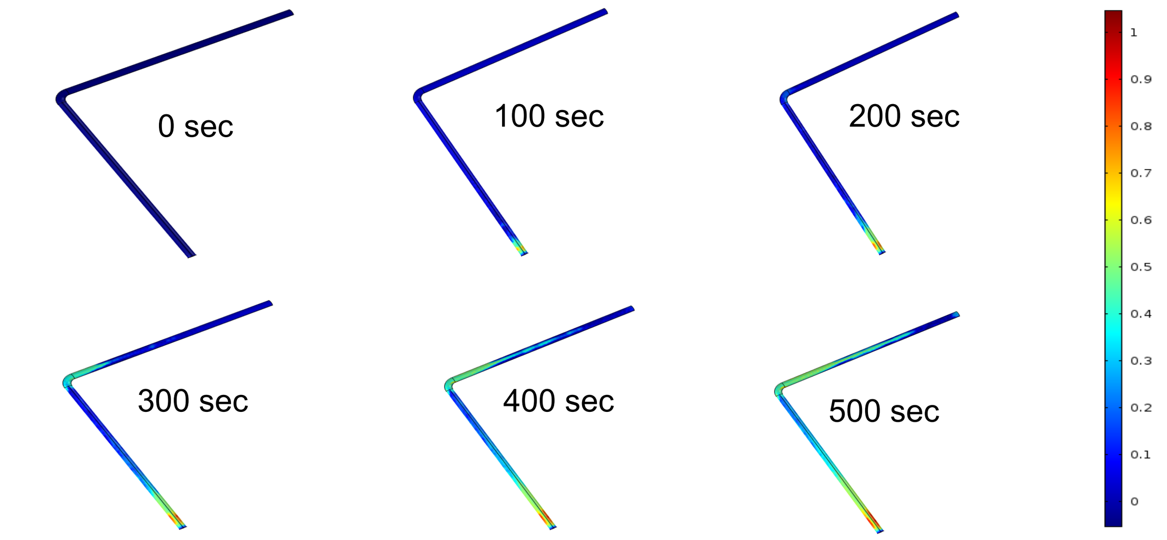


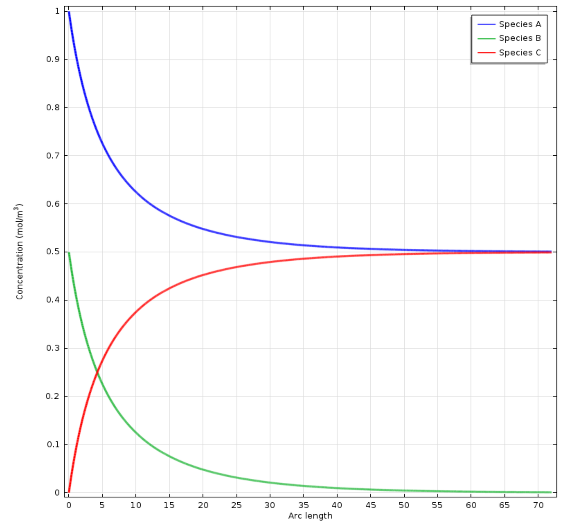
The numerical results were compared with experimental results with water as the carrier fluid entering a horizontal pipe of 0.04 m diameter and 28 m in length. The numerical results matched closely with the experimental data.



As the flow enters the elbow, it deviates from its primary path and accelerates towards the inner wall of the elbow. This in turn creates a secondary flow which reaccelerates towards the outer wall of the downstream pipe. The acceleration and reacceleration results in formation of high velocity zones as highlighted by red color streamlines.

CHEMICAL REACTION MODELING (A+B→C)



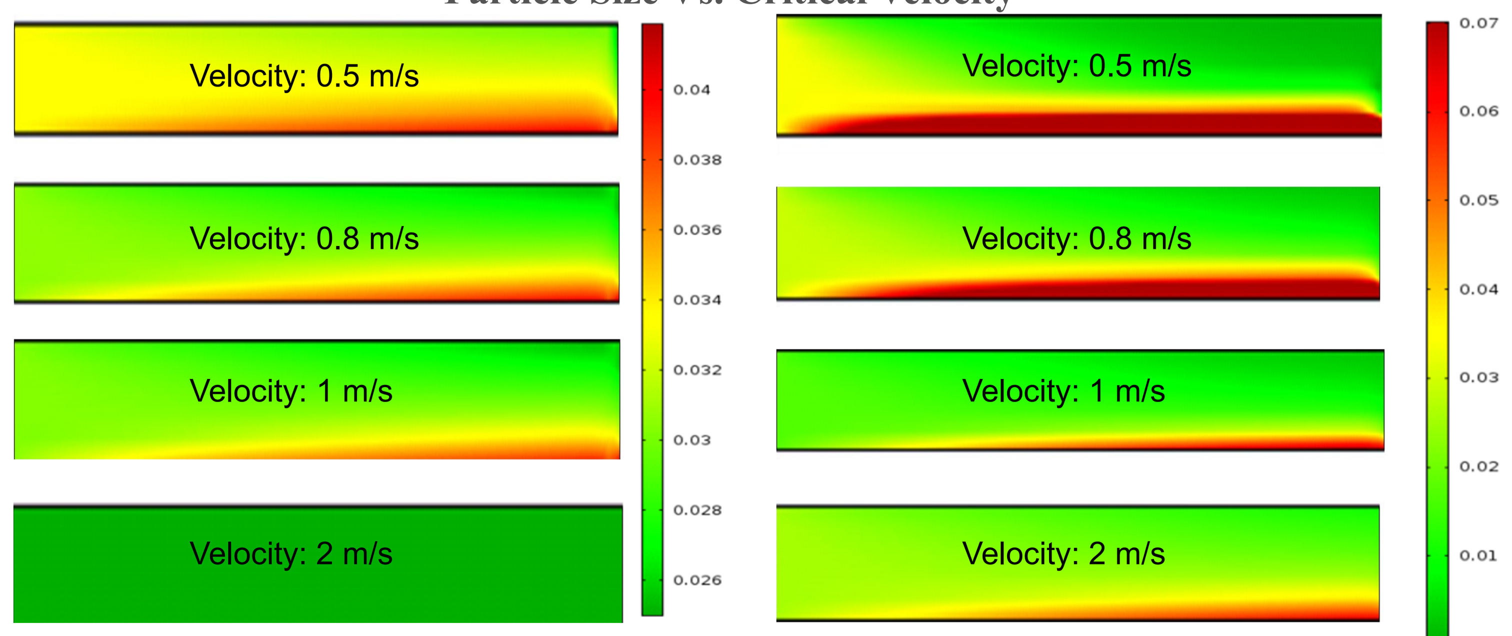


For the chemical reaction modeling simulations, the solved flow field from flow modeling simulations was used as an input to simulate the coupled flow chemical interactions. The transition of the species from the reactants to product as they underwent a chemical reaction at time intervals of 0, 100, 200, 300, 400 and 500 seconds is shown in the above figure. The concentration of product species was found to be the highest at the inner wall of the elbow as the flow moved towards the outlet. This was due to the higher velocity observed in those areas. The residence time of the reactants was lower at the higher velocity areas resulting in the production of species C in those sections. This was characterized by an increased concentration of product species C (red color) observed at the inner wall of the elbow and thereafter.

The figure above shows a typical progress curve for the chemical species undergoing a irreversible reaction in a pipe. The concentration of the reactants species A and B decreases as they get consumed. At the same time the concentration of product species C increases as it gets produced.

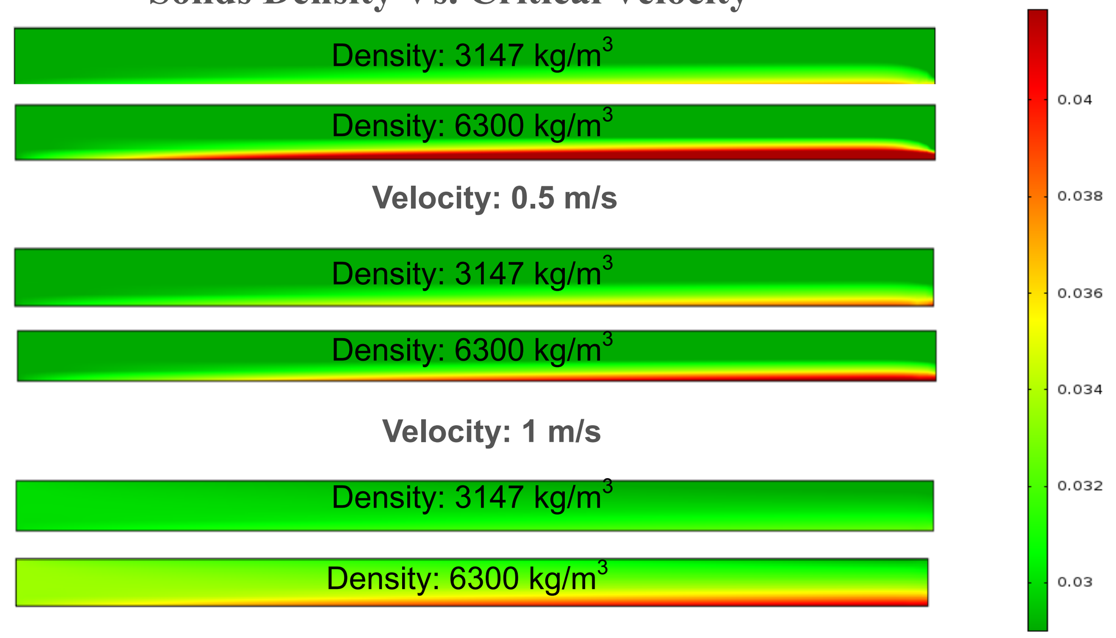
TWO PHASE FLOW MODELING

Particle Size Vs. Critical Velocity



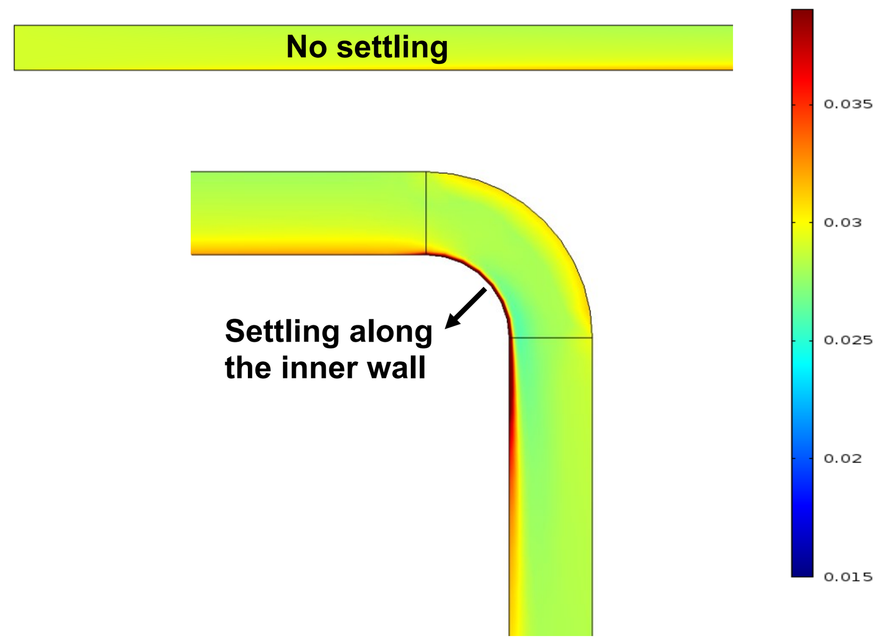
The results above show that the 220 µm heavier particles tend to settle fast on the bottom of the pipe, especially at low flow velocities. For flow velocities lower than 1.0 m/s, a stationary bed is observed that eventually causes a plug to form. For velocities greater than 1.0 m/s, the fluid establishes a moving bed regime where the particles move along the bottom of the transfer pipe.

Solids Density Vs. Critical Velocity



The results above show that the higher density slurries require a higher velocity to keep them suspended and prevent them from settling at the bottom compared to the lower density slurries. The critical velocity for the slurries with density of 3147 kg/m^3 was 1 m/s compared to the 4 m/s velocity obtained for the heavier slurries with density of 6300 kg/m^3.

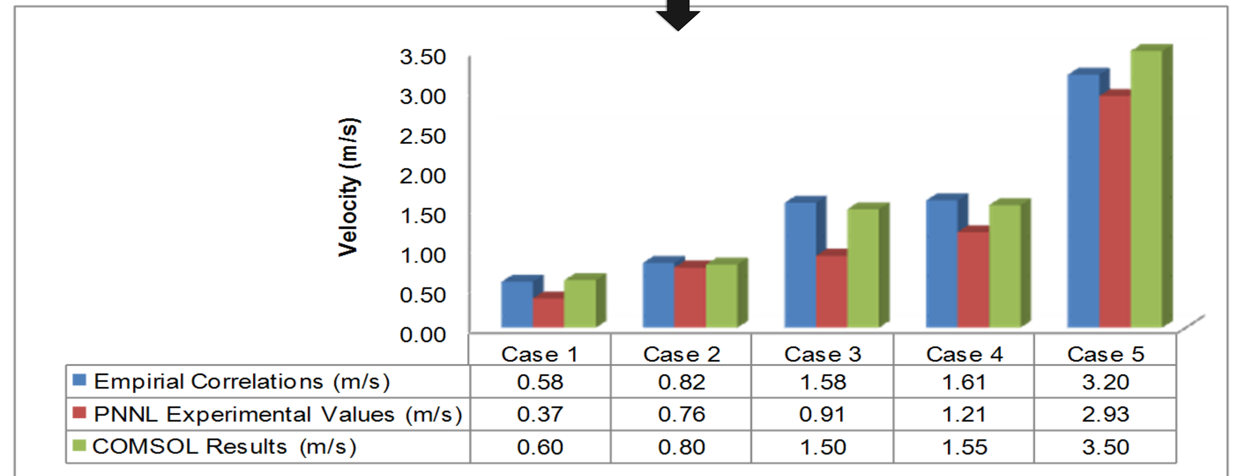
Influence of Elbow on Settling of Solids



The simulations investigating the influence of elbow on the settling of solids show that solids are seen deposited along the inner wall of the elbow due to the dead flow zones developed in that area.

NUMERICAL COMPARISON

	Model Verification Study				
Test Configuration	Case 1	Case 2	Case 3	Case 4	Case 5
Particle diameter (µm)	14.4	37.7	129.5	182.3	203.9
Solids Density (kg/m3)	2500	7950	3770	2500	7950
Solids volume fraction (%)	9.8	9.3	8.7	7.4	3.0
Liquid density (kg/m3)	1146	1647	1151	999	1026



The numerical results were a good match with the experimental results and demonstrated the use of COMSOL Multiphysics 4.3b to accurately simulate the settling physics.

FUTURE WORK

- Future work will include simulating plug formation via precipitation kinetics and investigate the chemical flow relationships.
- The models will also be simulated evaluating the influence of pipeline components on the settling dynamics.

REFERENCES

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