Simulation of Yield-Stress Fluid in a Rotational Rheometer:

The Effect of Vane Geometry on the Accuracy of Measured Properties

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Introduction: A rotational rheometer (ICAR rheometer : International Center for Aggregate Research at UT Austin) for Self-Consolidating Concrete (SCC) [1] was simulated as a yield-stress fluid in a 2D geometry to study the effects of the solver method and the vane geometry on the torque vs rotational velocity relation, the flow pattern, and the shear stress distribution.

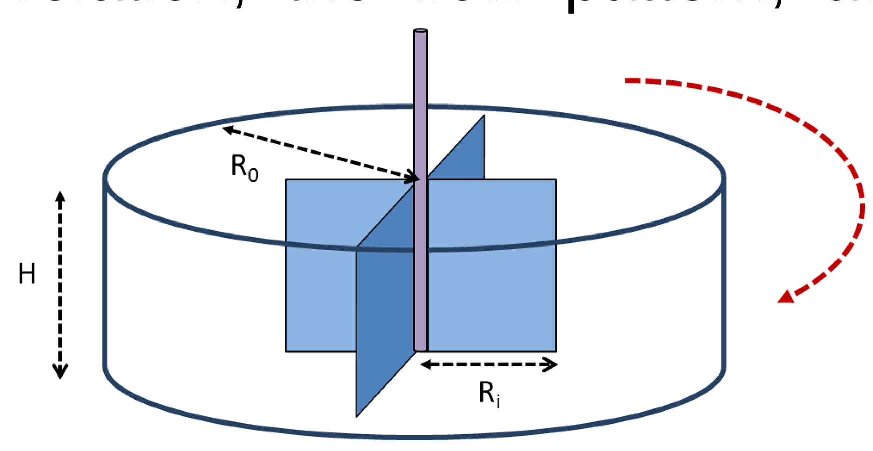


Figure 1. Schematic diagram of the rotational (ICAR) rheometer.

Computational Methods: The SCC flow was simulated as a single phase incompressible (ρ=2350kg/m^3) yield-stress fluid in a laminar flow regime. The expression for the shear stress is given by Bingham model with a numerical correction factor, ε=10^{-15}s^{-1}, to prevent zero shear rate [2,3].

$$\boldsymbol{\tau} = \left(\mu_p + \frac{\tau_y}{\sqrt{\dot{\gamma}^2 + \varepsilon^2}}\right)\Delta$$

Yield stress: τ_y, Plastic viscosity: μ_p
deformation tensor: $\Delta = \nabla\mathbf{u} + (\nabla\mathbf{u})^T$
shear rate: $\dot{\gamma} = \sqrt{\frac{1}{2}\Delta:\Delta}$.

1. Choose a vane geometry (coaxial, # of blades, straight or curved? [e.g.Figure 2])
2. Choose a property of SCC (τ_y, μ_p)

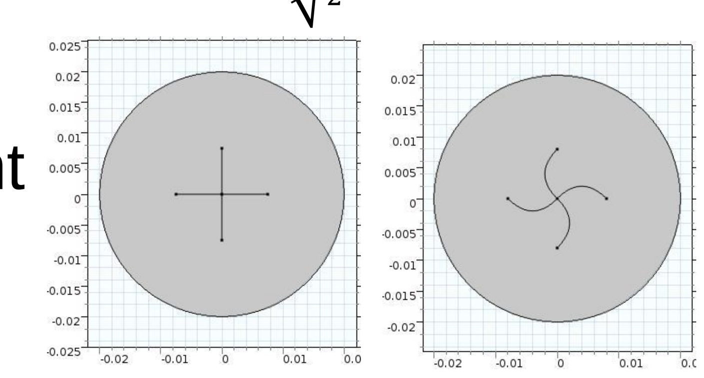


Figure 2. 4 straight and curved blades

3. Choose a solver method (Double dogleg or Newton?)
4. Choose N (rotational velocity in rpm)
5. Solve for flow and stress distributions
6. Calculate T/H (torque/height) by line integration
7. Compare with the analytical solution for coaxial cylinders [4]:

$$\frac{T}{H} = \frac{4\pi (R_o R_i)^2}{({R_o}^2 - {R_i}^2)}\left[\ln\left(\frac{R_o}{R_i}\right)\tau_y + 120\pi\mu_p \mathrm{N}\right]$$

Results 1: Simulation for SCC flow between coaxial cylinders (The effect of the solver method)

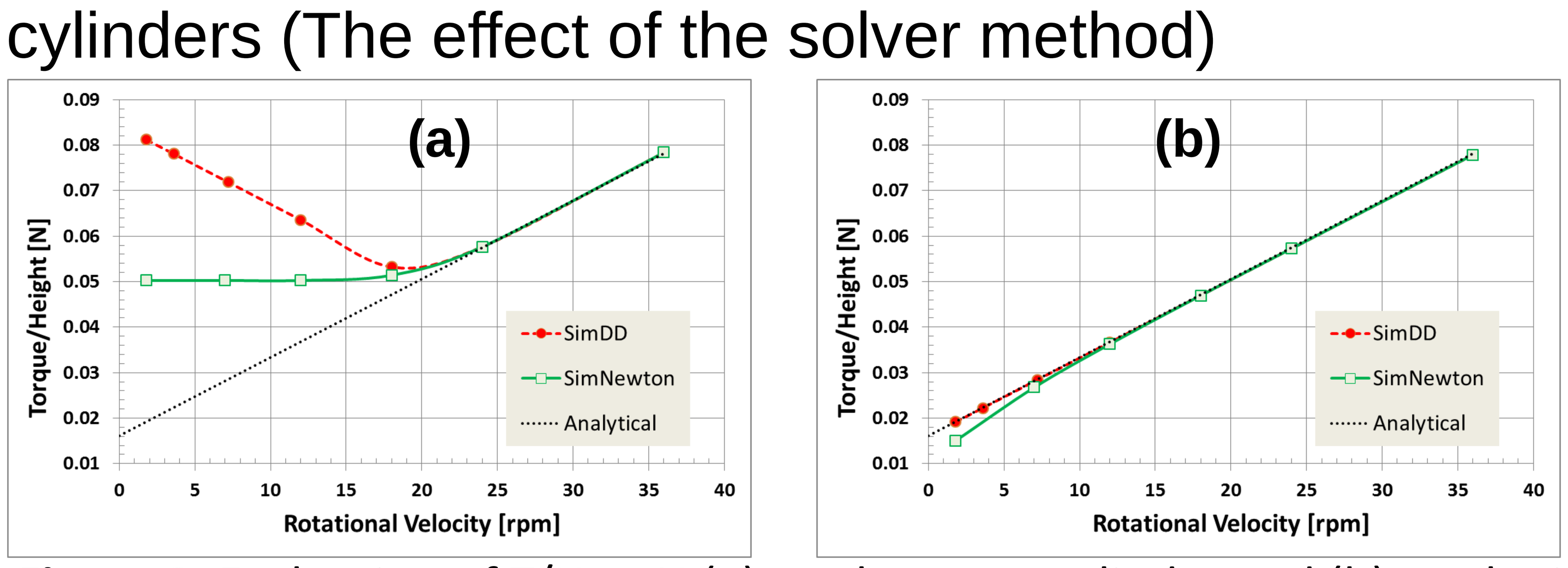


Figure 3. Evaluation of T/H vs N (a) on the outer cylinder and (b) on the inner cylinder of SCC flow with τ_y=20Pa and μ_p=20Pa·s. The unrealistic results in (a) are due to the unyielded zone (Figure 4b).

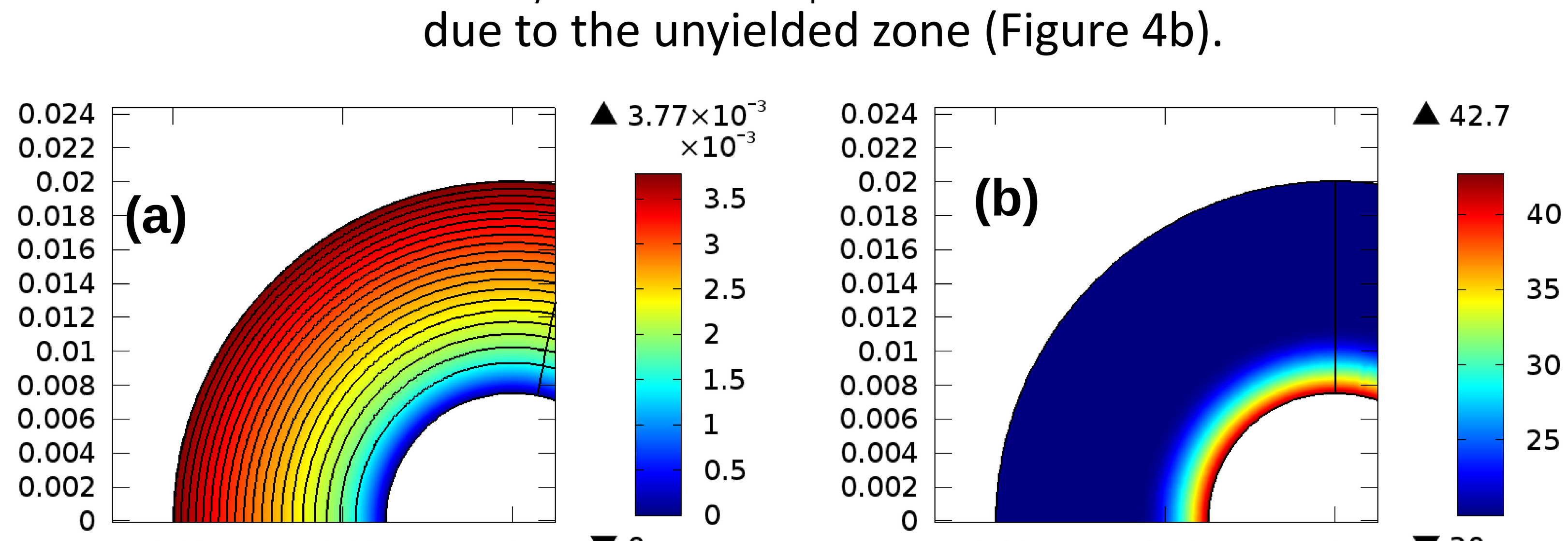
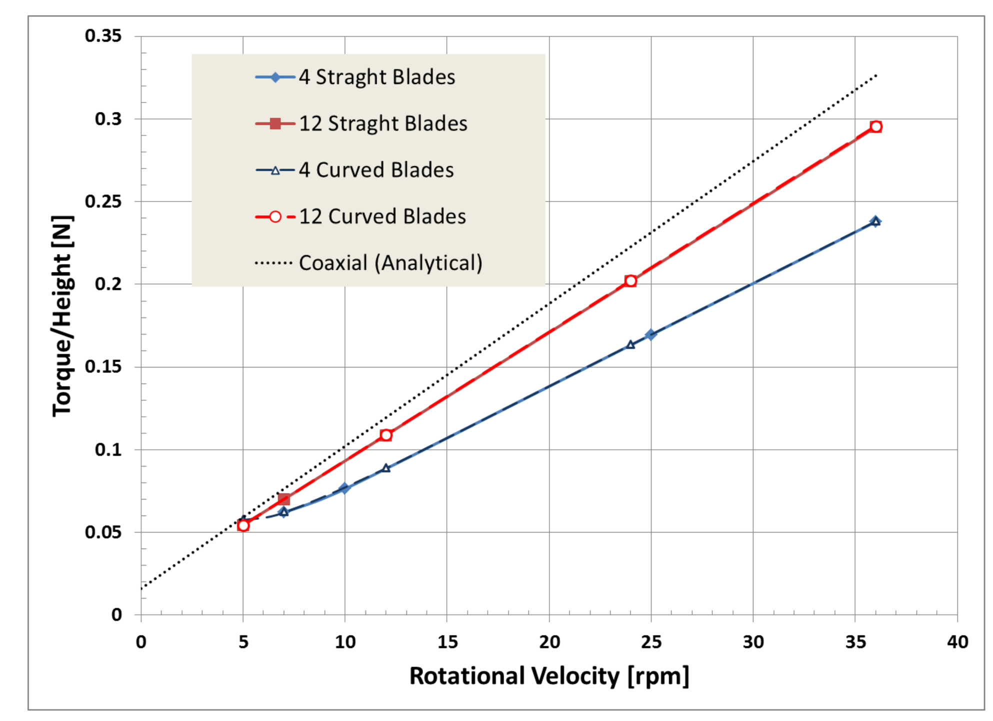


Figure 4. (a) Flow pattern and (b) shear stress map of SCC flow under N=1.8rpm obtained from the Newton method. Double dogleg method gave the convergent solution very fast but the flow and stress map at low N show unphysical behaviors.

Results 2: Simulation for SCC flow with blades (The effect of the vane geometry)



The results from both the curved and the straight blades are almost identical (The effect of the blade curvature is negligible) due to the very similar flow patterns: data not shown.

Figure 5. Evaluation of T/H as a function of N for various vane geometries (blue: 4 blades; red: 12 blades; black: analytical coaxial cylinders). The material properties of SCC are τ_y=20Pa, μ_p=100 Pa·s.

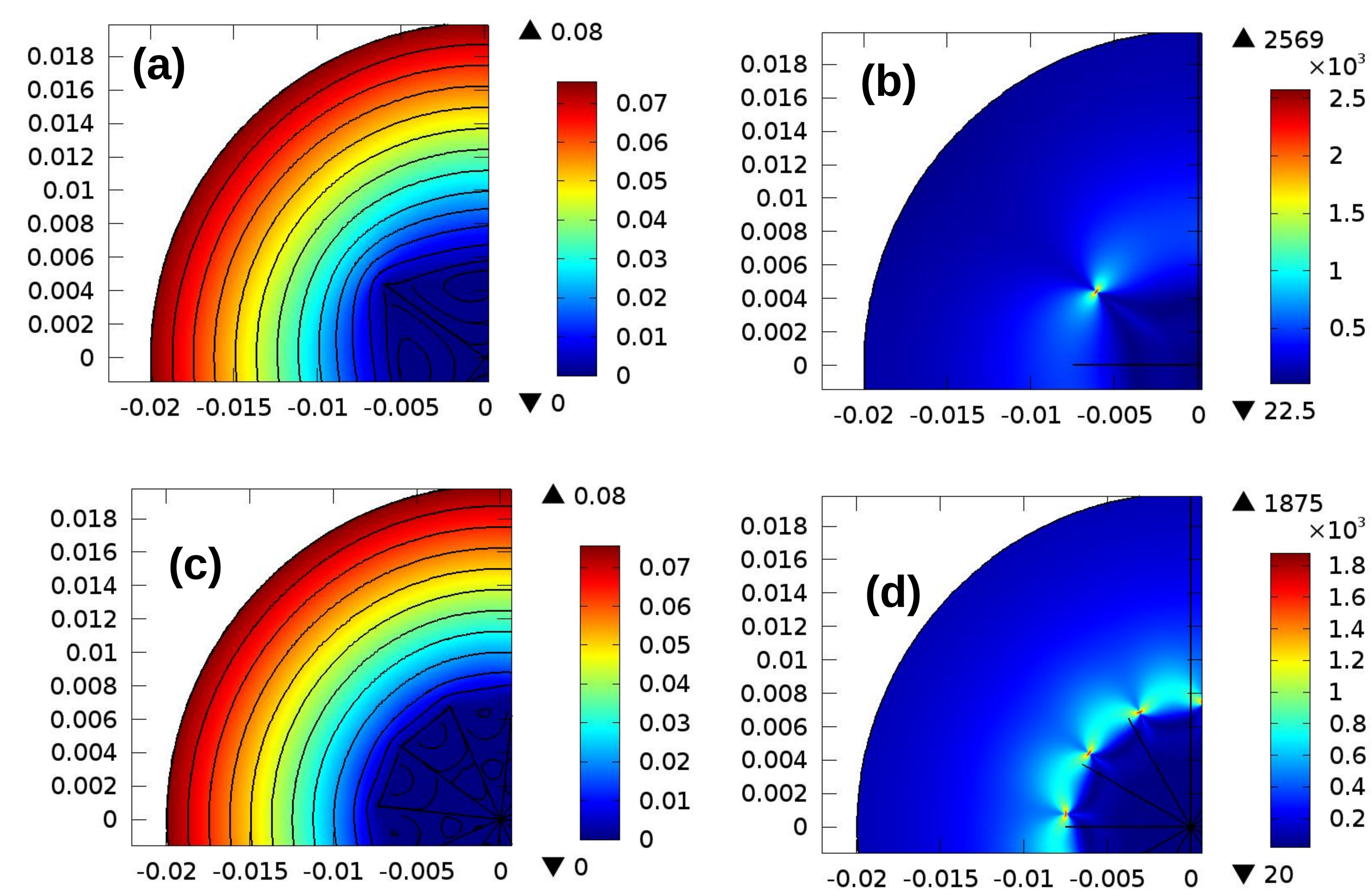


Figure 6. (a,c) Flow pattern and (b,d) shear stress maps of SCC flow with τ_y=20Pa and μ_p=20Pa·s under N=1.8rpm. Square-shape unyielded zone (a) and localized stress (b) of 4 blades caused the slope less than that of the analytical solution in Figure 5. As the number of blades increases to 12 (c,d), the velocity and stress patterns become closer to those of coaxial cylinders in Figure 4, which resulted in the increased slope in Figure 5.

Conclusions:

- T/H vs N obtained on the outer surface of cylinder showed the unphysical behavior due to occurrence of the unyielded zone.
- Newton method gave physically plausible flow pattern with difficulty of convergence while Double dogleg method gave unphysical behavior with fast convergence.
- The flow pattern and the T/H vs N trend are independent of the curvature of the blade but sensitive to the number of blades.

References:

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