# Transport Effects in Cellulose Fiber Beds Using Magnetic Resonance Imaging

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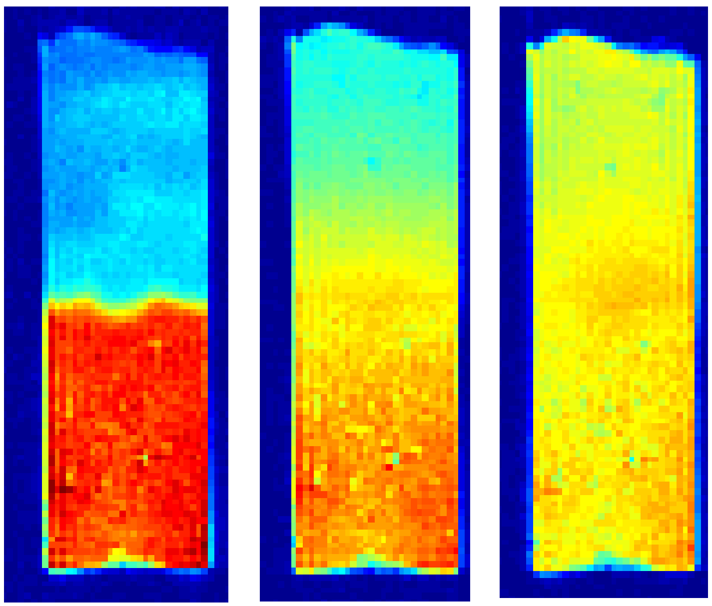

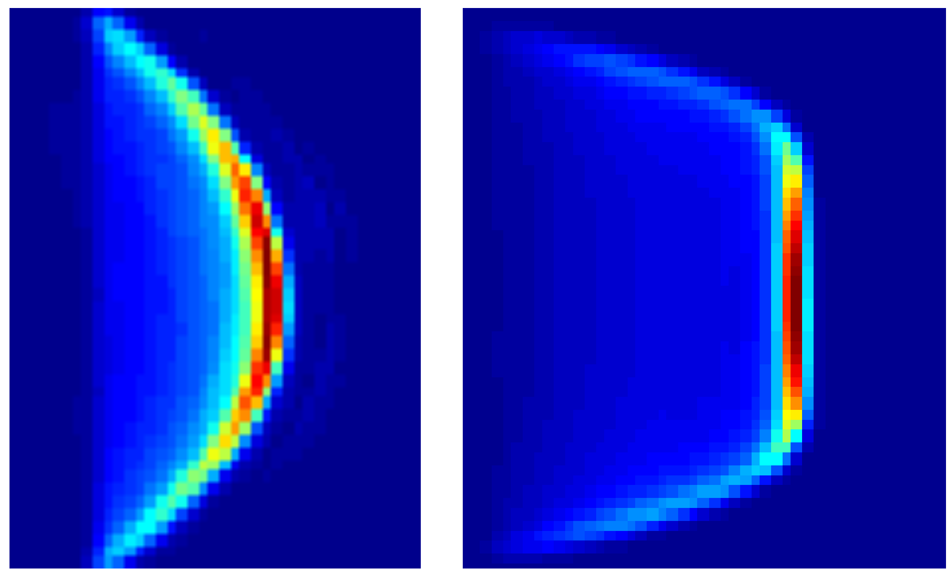

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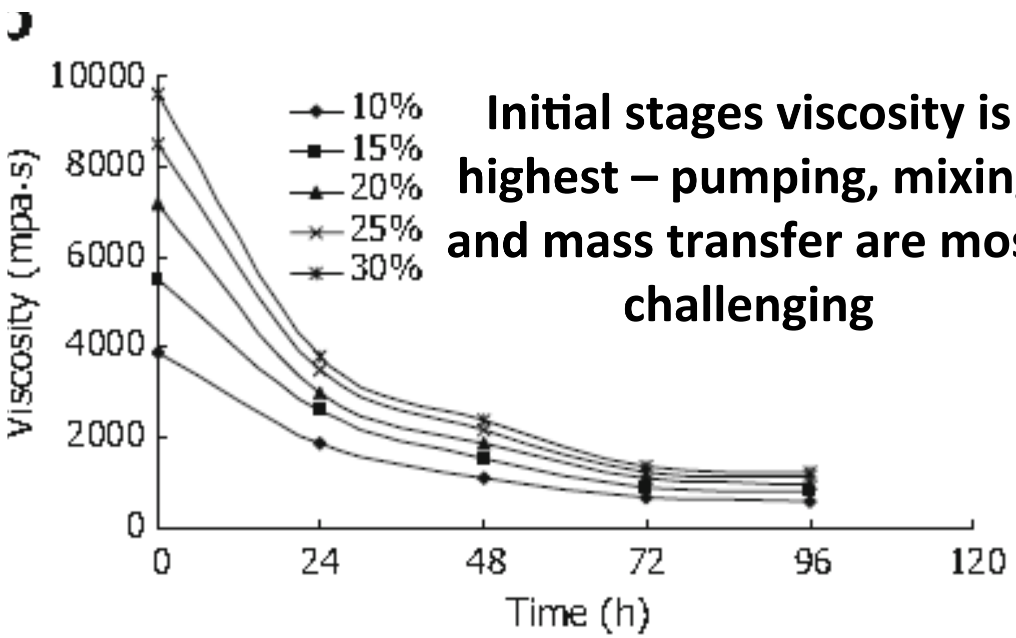
# Outline

- Biomass Processing
- MRI
- Diffusion & Adsorption
- Fluid Mechanics & Rheology
- Conclusions

# Some Issues

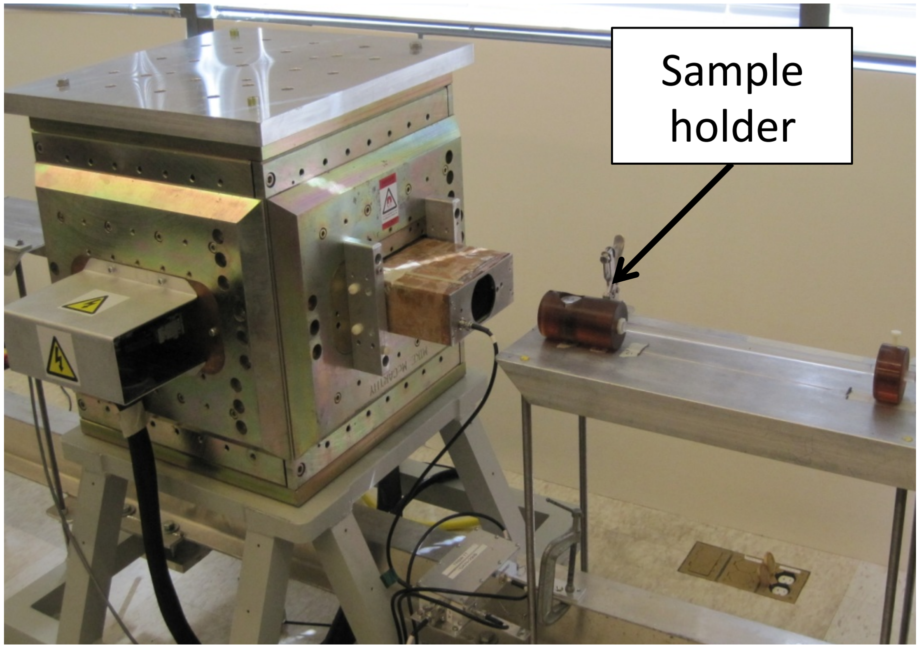
- High cellulose content implies poor mixing of enzyme and cellulose during hydrolysis




**Initial stages viscosity is highest – pumping, mixing and mass transfer are most challenging**

# Goals

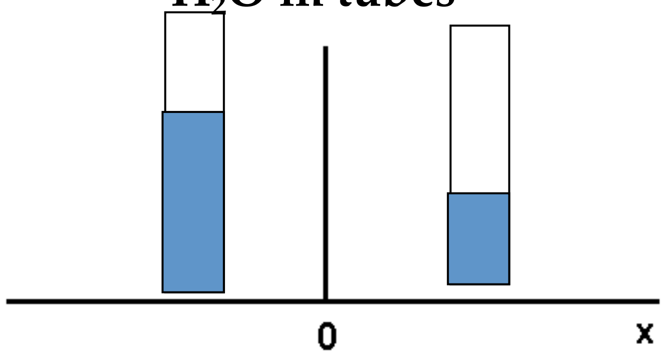
- Use diffusing molecules with similar adsorption behavior and molecular weight as enzymes
- Measure diffusion in various cellulosic fiber beds
- Measure yield stress
- Use **magnetic resonance imaging** (MRI)



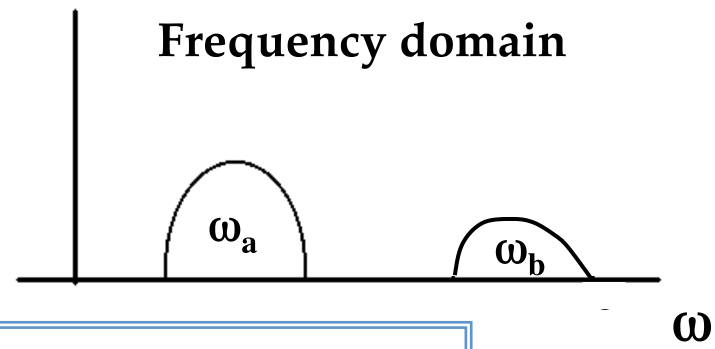

1T Aspect permanent magnet shown above; cartoon of sample holder and magnet below.

# MRI

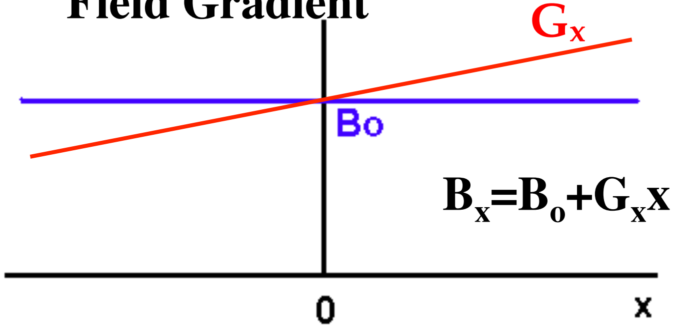
$H_2O$ in tubes




Transform Frequency into Spatial Information



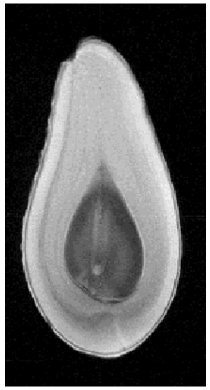

Linear Magnetic Field Gradient

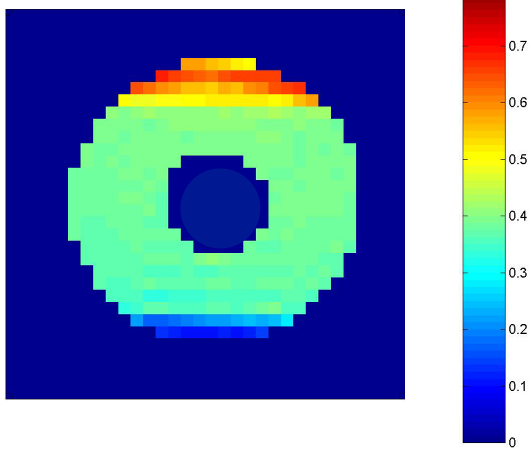



Magnetic field

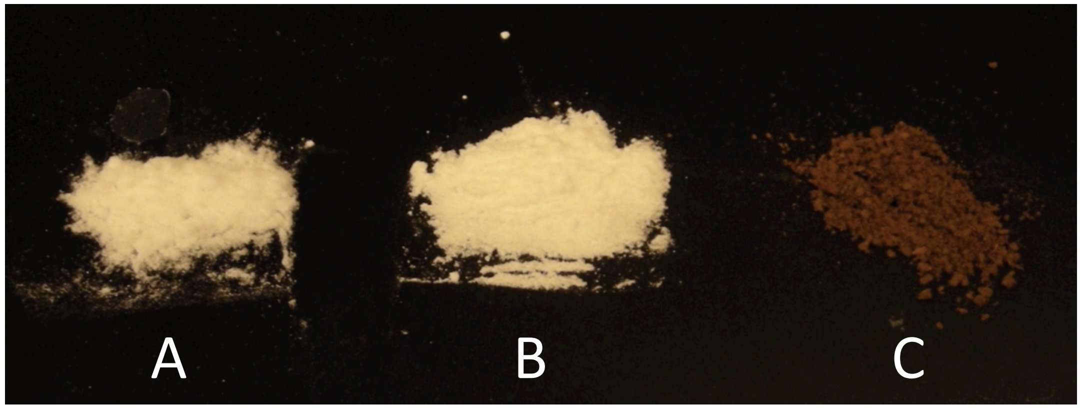
$$\Longrightarrow \quad \omega = \gamma\,(B_o + G_x\,x)$$

Larmor Relation

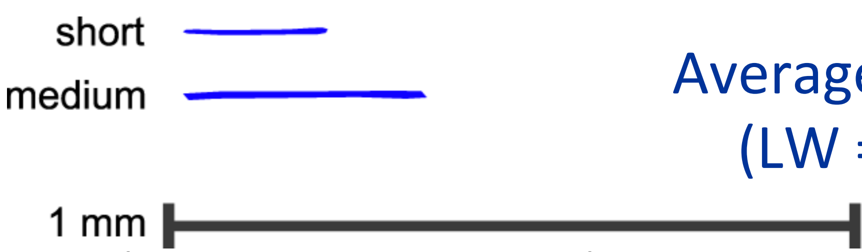




# Fibers



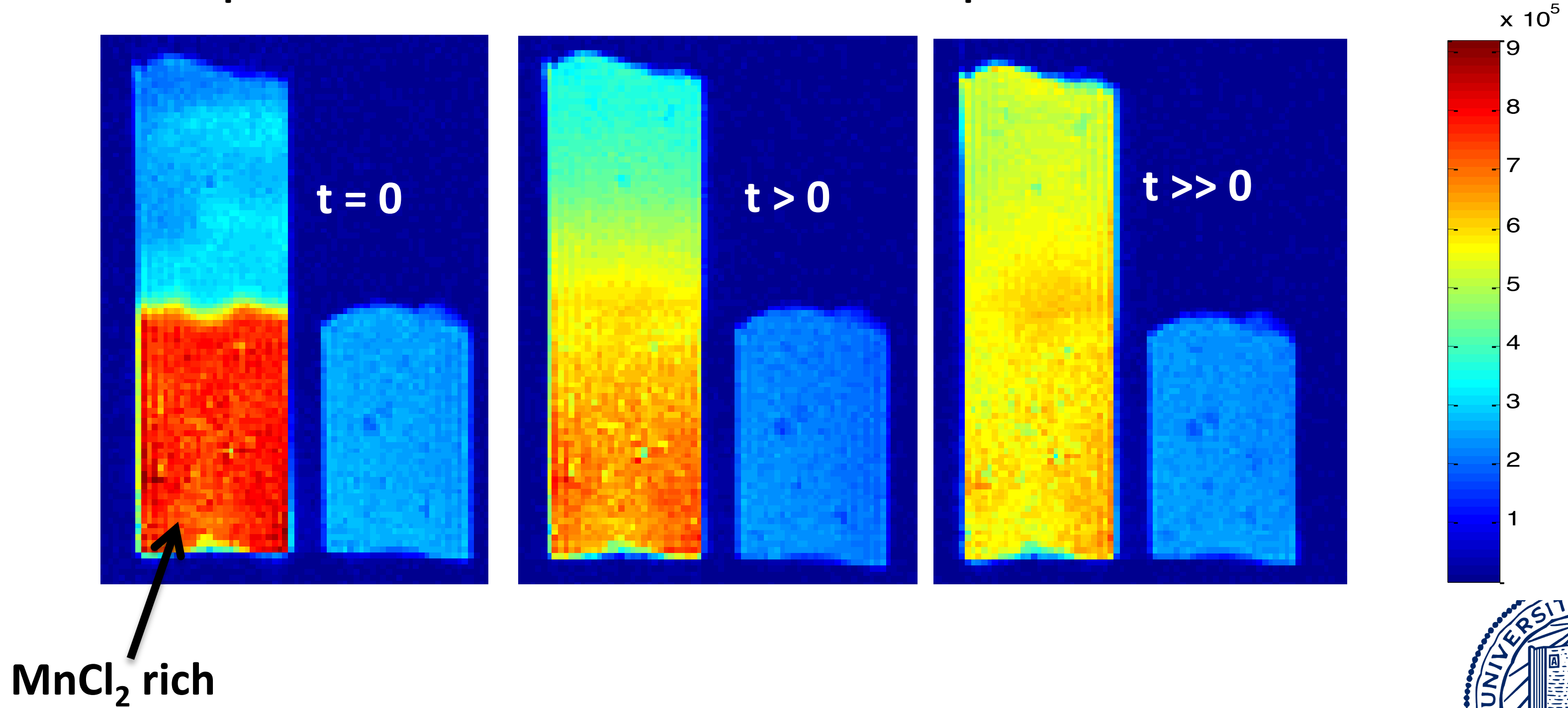

| Fiber type | Length (LW) | Length (NW) | Width (LW) |
|---|---|---|---|
| a) Solka-Floc 200EZ | 0.207 mm | 0.183 mm | 26.4 µm |
| b) Solka-Floc C100 | 0.349 mm | 0.273 mm | 31.7 µm |
| c) NREL PCS | - | - | - |



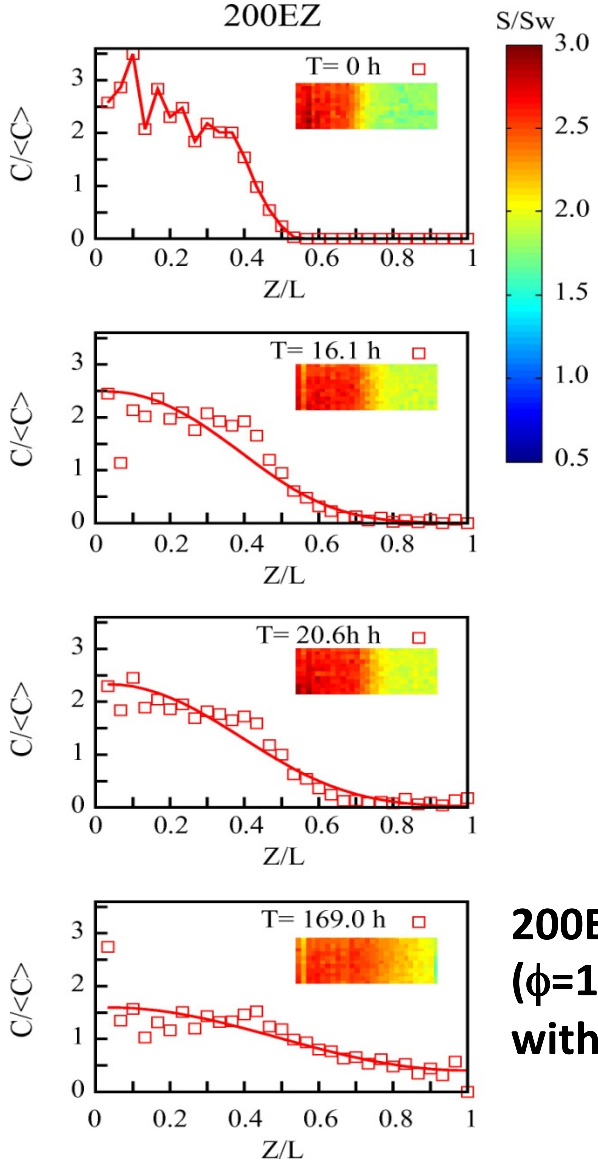

Average length of fibers used
(LW = Length Weighted)

# Images and Analysis

- Images taken at various time points
- Concentrations determined from calibration relationship
- Crank-Nicolson finite difference numerical solution used to match experimental and numerical profiles

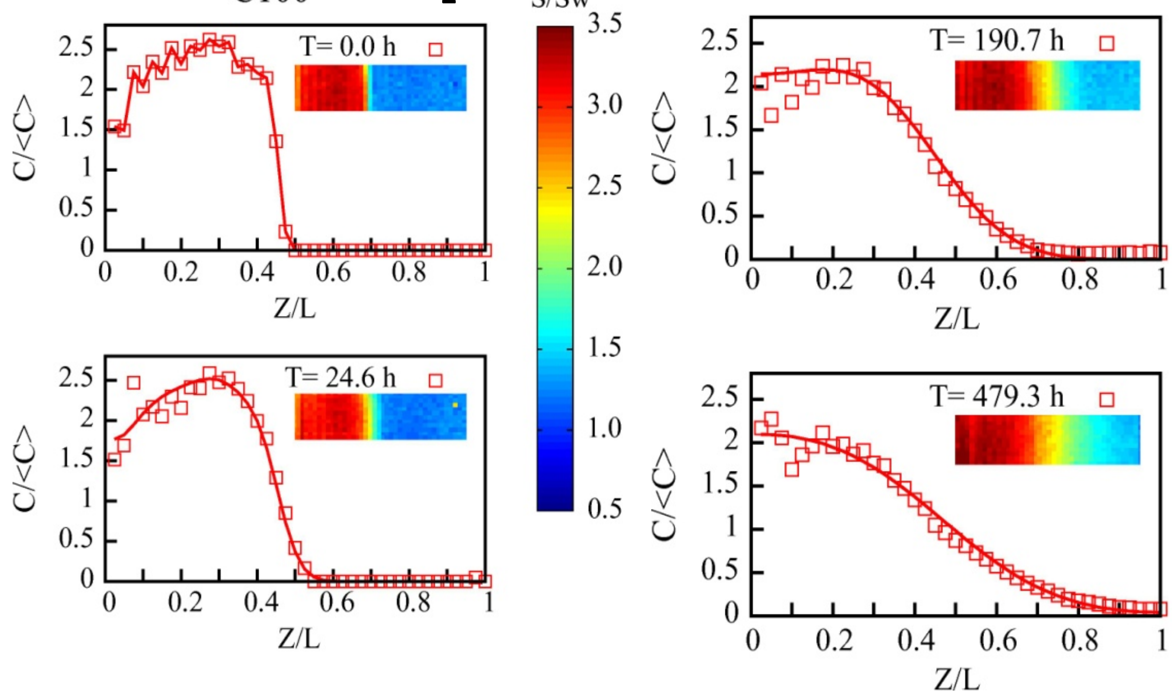


# Concentration Profiles




**200EZ Fibers ($\phi$=12%) with $MnCl_2$**

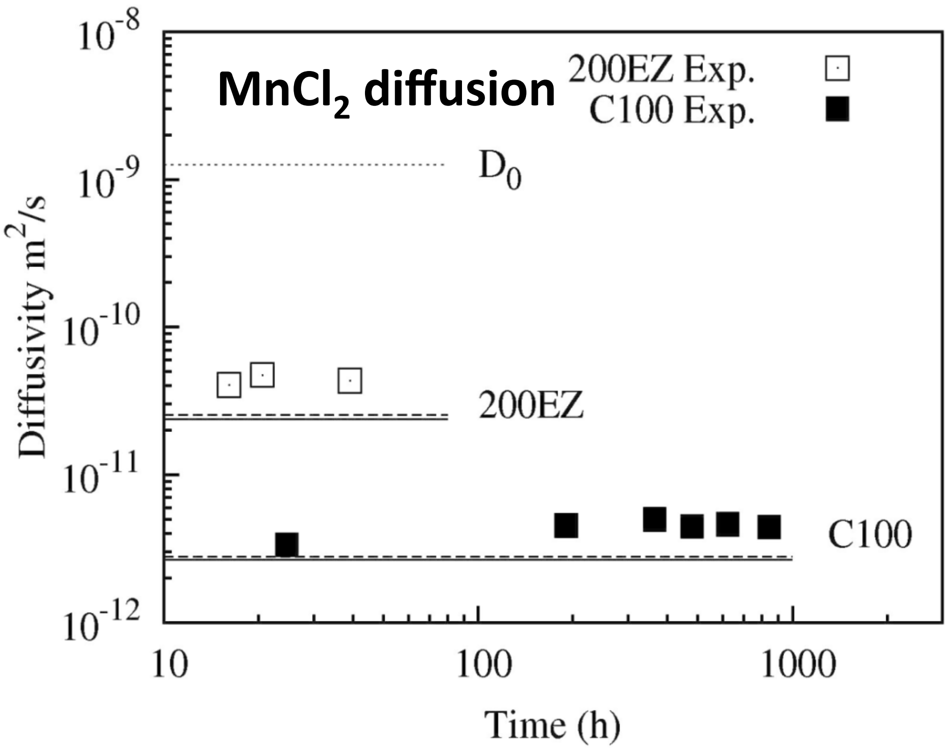
**C100 Fibers ($\phi$=9%) with $MnCl_2$**

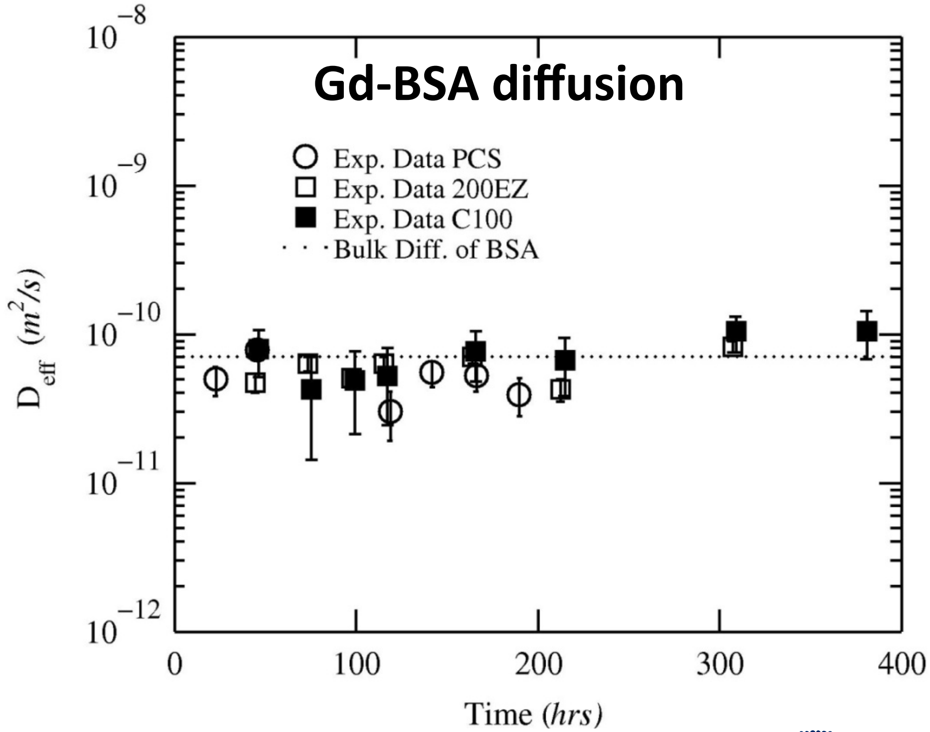



**<u>Numerical solutions match the experimental profiles</u>**

# Diffusion Model Summary

| Fiber | C100 | | 200EZ | | PCS | | Bulk, $D_0$ |
|---|---|---|---|---|---|---|---|
| | Exp. | Model | Exp. | Model | Exp. | Model | |
| $D_{MnCl_2}$, $m^2s^{-1}$ | 4.39x$10^{-12}$ | 2.79x$10^{-12}$ | 4.37x$10^{-11}$ | 2.56x$10^{-11}$ | - | - | 1.26x$10^{-9}$ |
| $D_{BSA}$, $m^2s^{-1}$ | 7.07x$10^{-11}$ | 6.10x$10^{-11}$ | 5.98x$10^{-11}$ | 5.81x$10^{-11}$ | 5.05x$10^{-11}$ | 5.18x$10^{-11}$ | 7.00x$10^{-11}$ |

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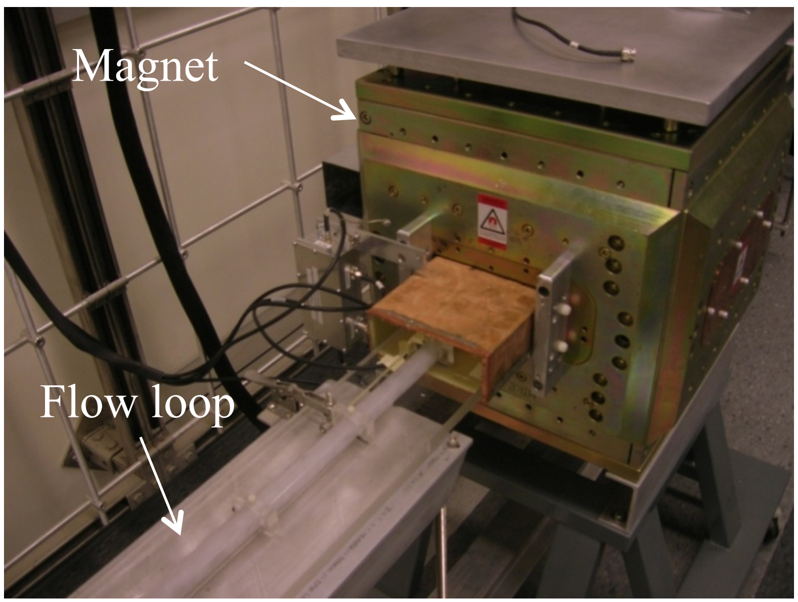
# Rheology

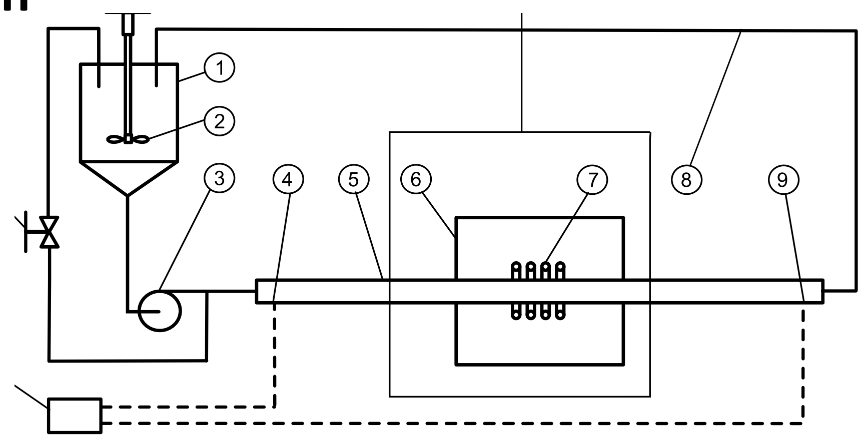
- Recent biomass literature
  - Non-Newtonian behavior
    - Shear-thinning and a yield stress
  - Understand rheology of suspensions during biomass digestion (enzymatic hydrolysis)
- MRI Flow Imaging
  - Effective in-line rheometer for rheological measurements

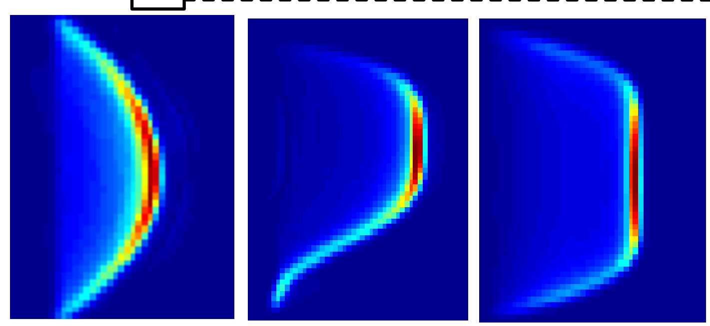
# Velocity Measurements via MRI

- **1T Aspect permanent magnet based spectrometer**
  - 30 G/cm peak gradient strength
  - 38x36 mm cylindrical coil
  - 2.08 m long, 19mm diameter pipe
- **Pulsed gradient spin echo sequence with velocity encoding**

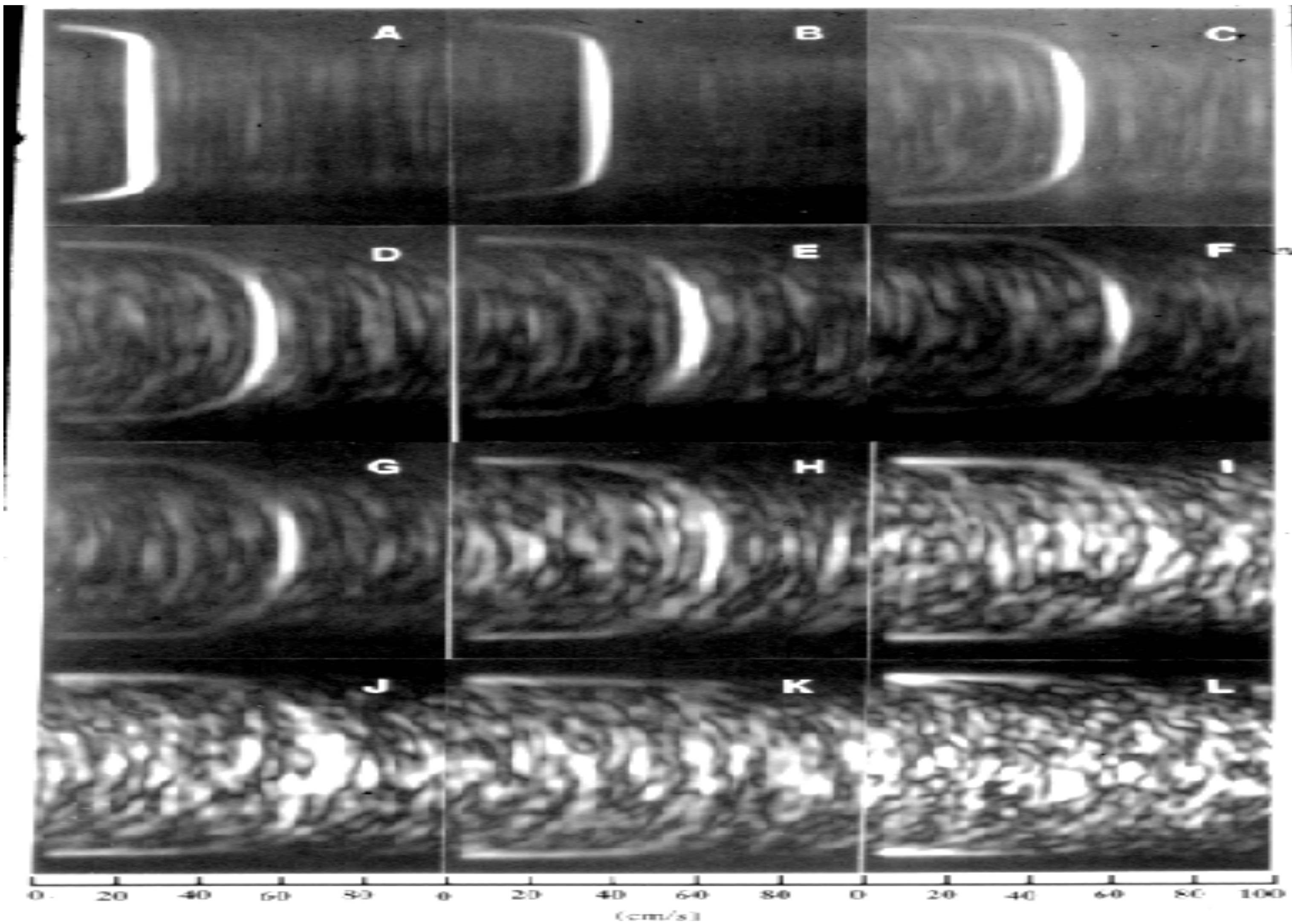



- Resolve settling, asymmetry, and plug flow profiles of high solids suspensions
- Simultaneously measure pressure drop across the pipe



# 0.5% Hardwood Pulp Suspension

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# Viscosity Measurement

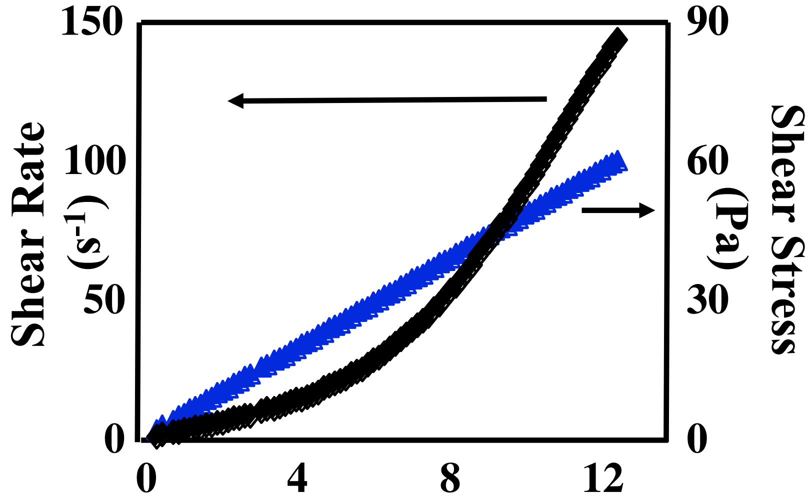
**Measure ΔP**

$$\sigma(r) = \frac{\Delta P}{2L} r$$

**Measure v(r)**

$$\dot{\gamma}(r) = \left| \frac{dv(r)}{dr} \right|$$

**Shear Viscosity** $$\eta(\dot{\gamma}) = \frac{\sigma(\dot{\gamma})}{\dot{\gamma}}$$

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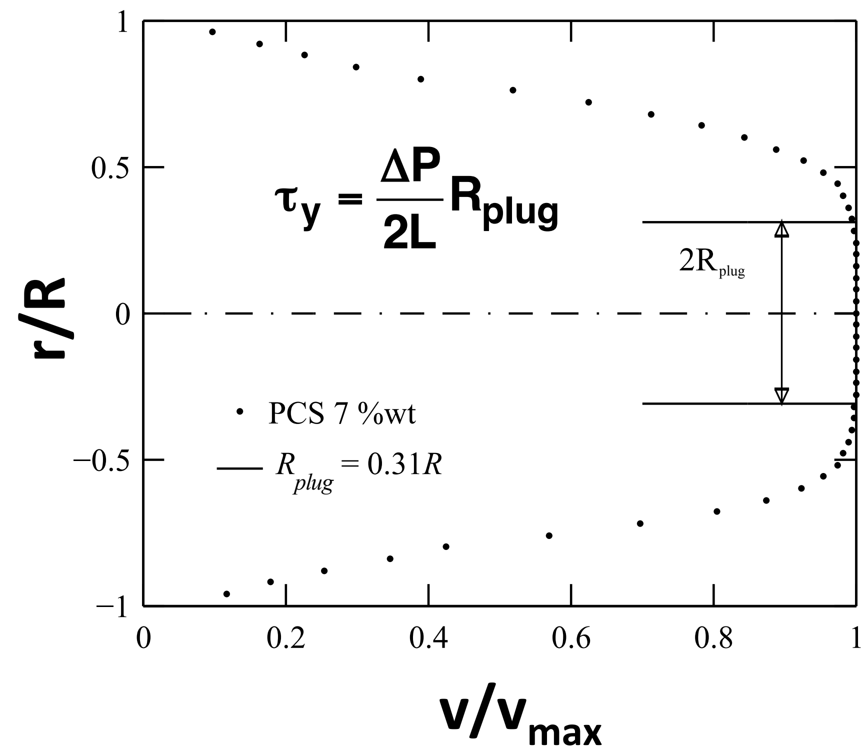
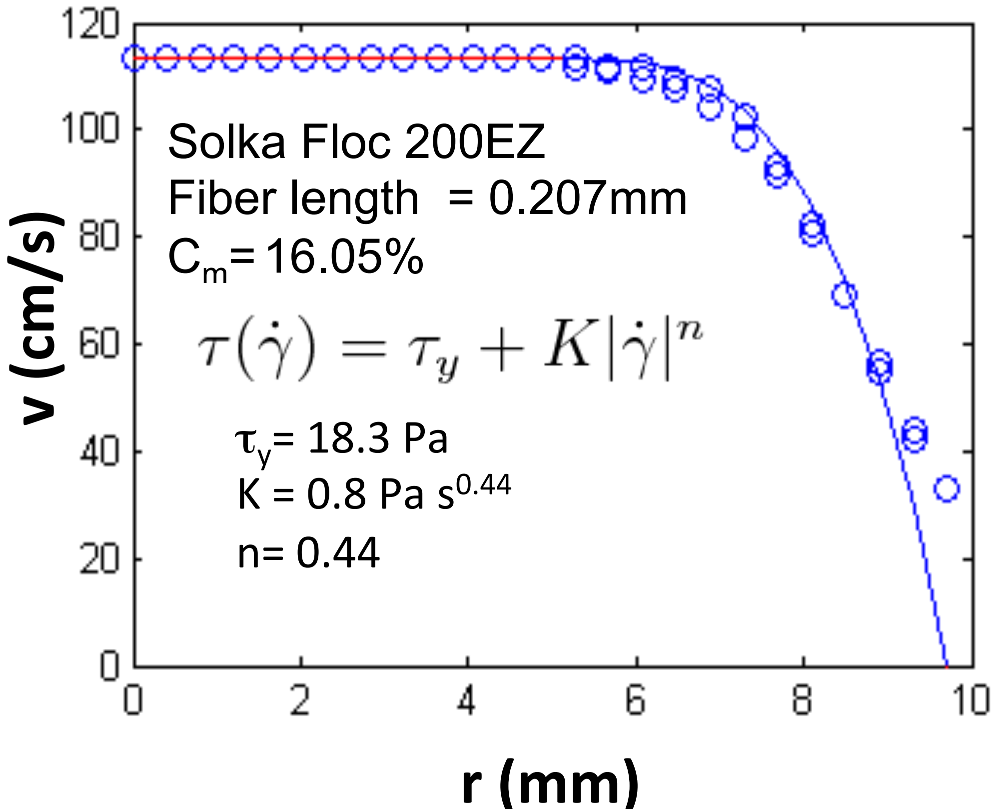
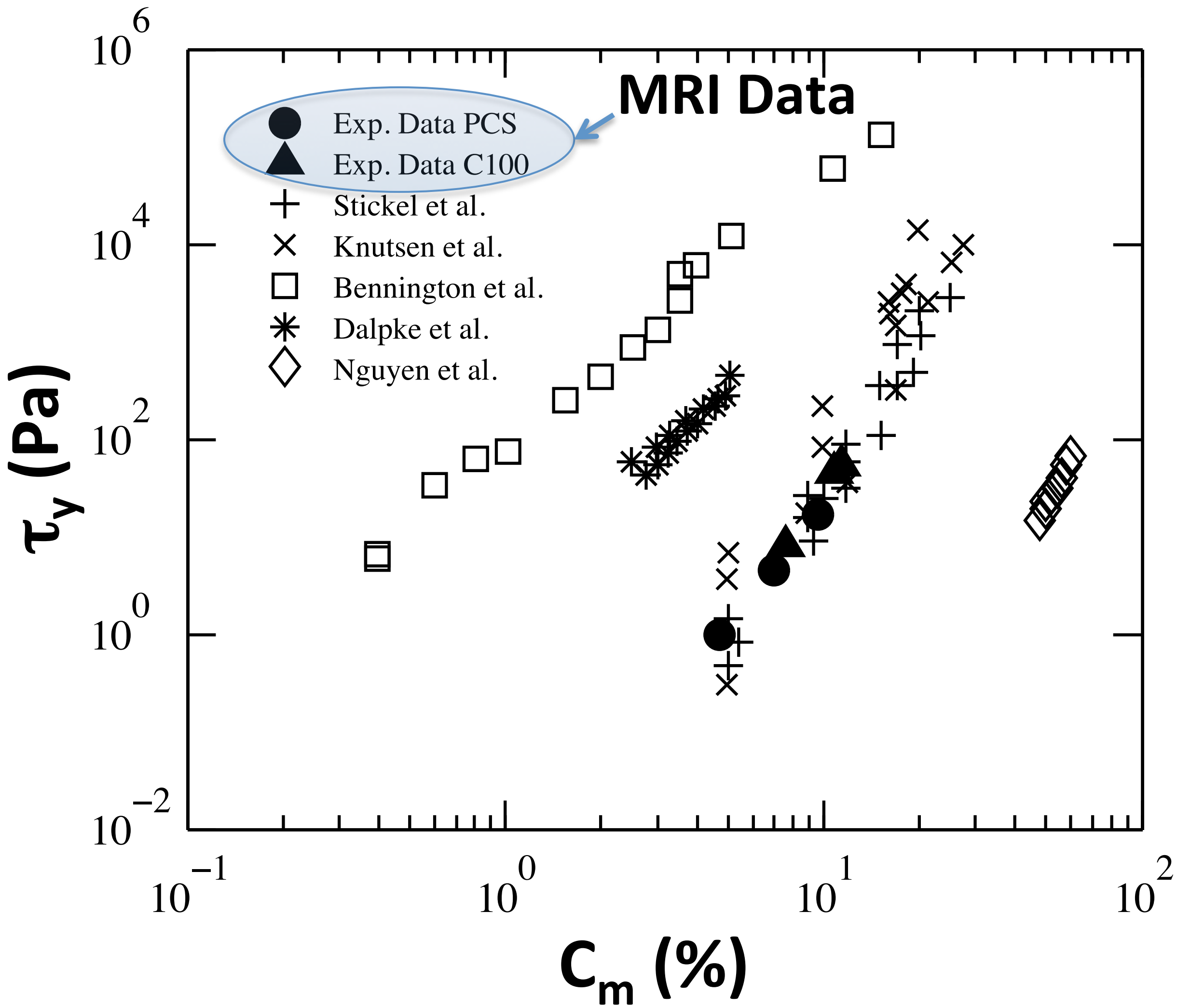
# Yield Stress



# Summary of Results



# Summary of Results

| Fiber Type | Length Dist. (mm) | $\sigma_0$ Range (Pa) | $C_m$ Range (%) | *a* | *b* | Reference |
|---|---|---|---|---|---|---|
| Semi-bleached pulp | 1.94–2.51 | 0.3 – $2.0x10^4$ | 0.004 – 0.4 | 99.7 | 2.45 | (Bennington et al. 1990) |
| Aspen & Birch pulp | 0.94–1.43 | 70 – 500 | 2 – 6 | 2.8 | 2.93 | (Dalpke & Kerekes 2005) |
| PCS | 0.001–2.0 | 1.0 – $5.0x10^4$ | 5 – 30 | $1.4x10^{-4}$ | 5.27 | (Stickel et al. 2009) |
| PCS | 0.001–3.0 | 0.1 - $1.0x10^4$ | 5 – 30 | $3.1x10^{-4}$ | 5.37 | (Knutsen & Liberatore 2009) |
| $TiO_2$ (“spherical”) | $2x10^{-4}$ | 10-100 | 50 - 70 | $1.0x10^{-10}$ | 6.55 | (Nguyen et al. 2006) |
| PCS (MRI) | 0.349 | 1.0 – 20 | 7 – 15 | $1.9x10^{-3}$ | 4.00 | |
| C100 (MRI) | 0.001-2.0 | 8.0 - 60 | 5 - 10 | $5.0x10^{-4}$ | 4.81 | |

# Conclusions

- Simple diffusion-adsorption model agrees well with experimental results
- Adsorption significantly hinders diffusion
  - Strong dependence on adsorption ($MnCl_2$)
- No measured adsorption of BSA on cellulose fibers
- Yield stress measured for PCS