Coal–Water Slurry technology: problems and modeling solutions

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Characteristics of the product

Mixture of coal (up to 70% in weight), water (up to 29%) and suitable fluidizing agents (about 1%). Coal particles are micronized with a top size of about 250 μm and a bimodal size distribution centered at 10 and 100 μm for optimal (maximum) packing.
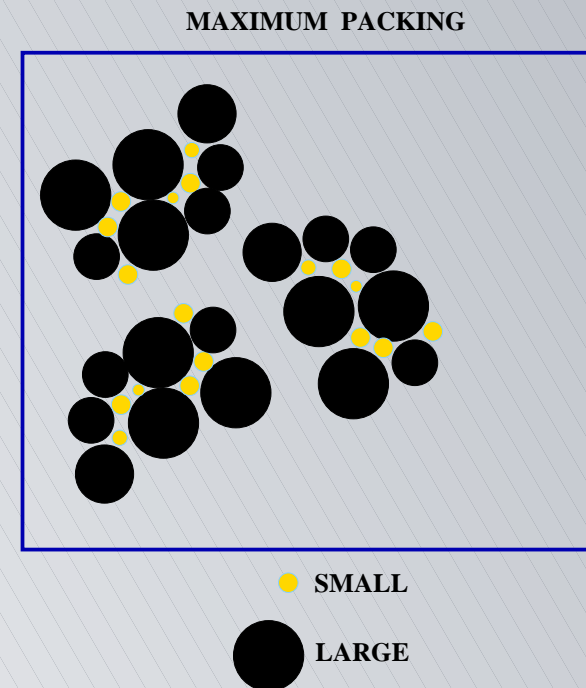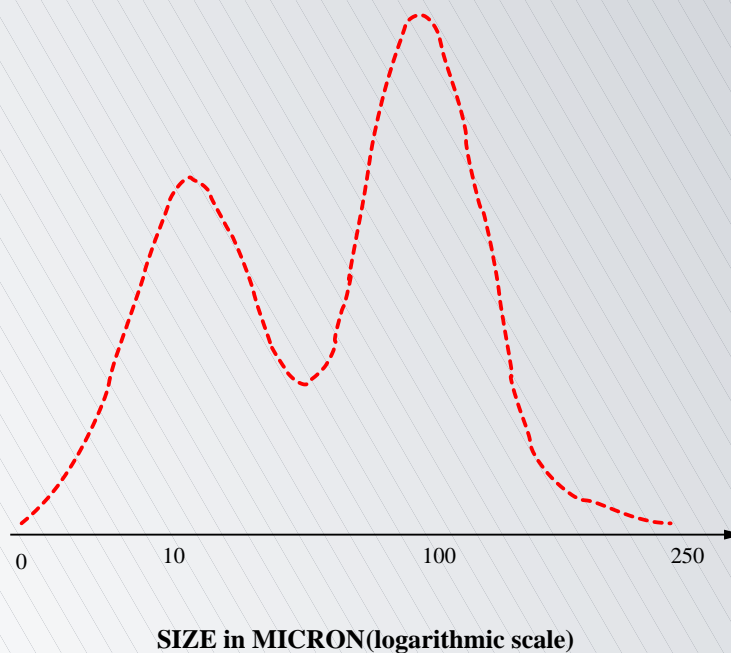
MAXIMUM PACKING

SIZE in MICRON(logarithmic scale)

● SMALL

● LARGE

Industrial problems

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- Sedimentation

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- **Rheological degradation**: it's a long-time effect due to shear. The apparent viscosity reaches extremely high values and the product becomes useless.

- **Sedimentation**: it's also a long-time effect due to manufacturing impurities which are not stabilized by chemical surfactant. A sedimentation bed grows up on the bottom of the first kilometers of a pipeline eventually compromising the optimal discharge

Degradation
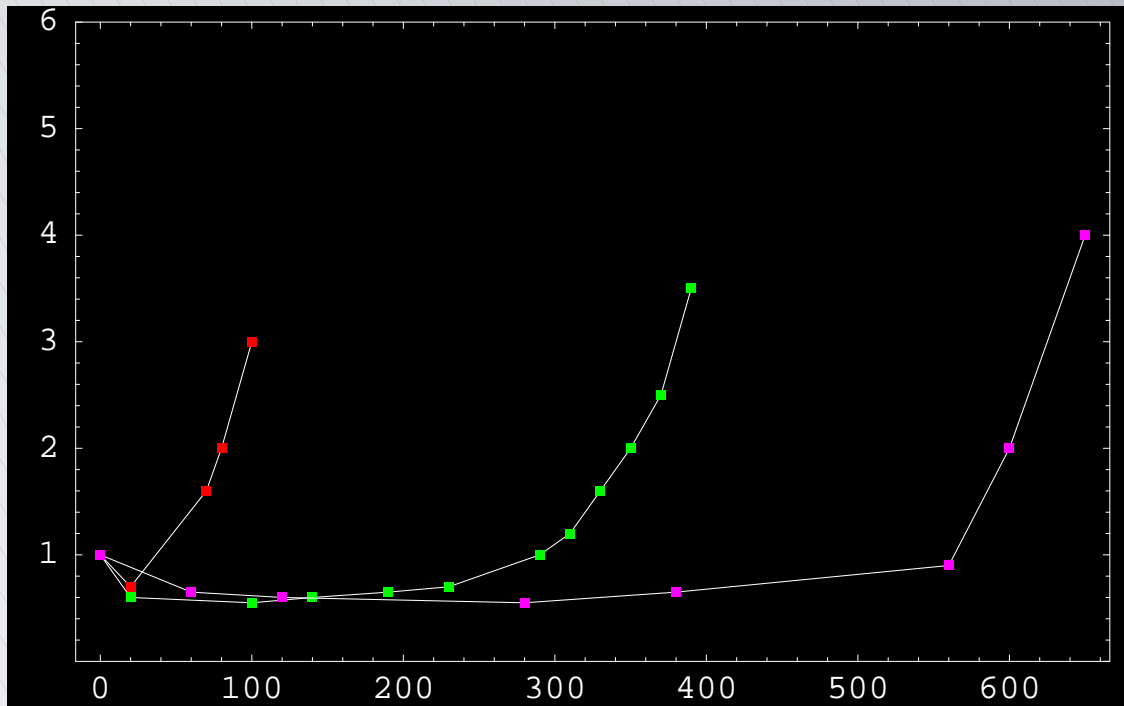
Relative apparent viscosity at $10\ s^{-1}$ vs. specific cumulative energy (kJ/kg) for a polish

CWS. The different marks identify mixtures with 0.5%, 0.75%, and 1.00% of dispersed
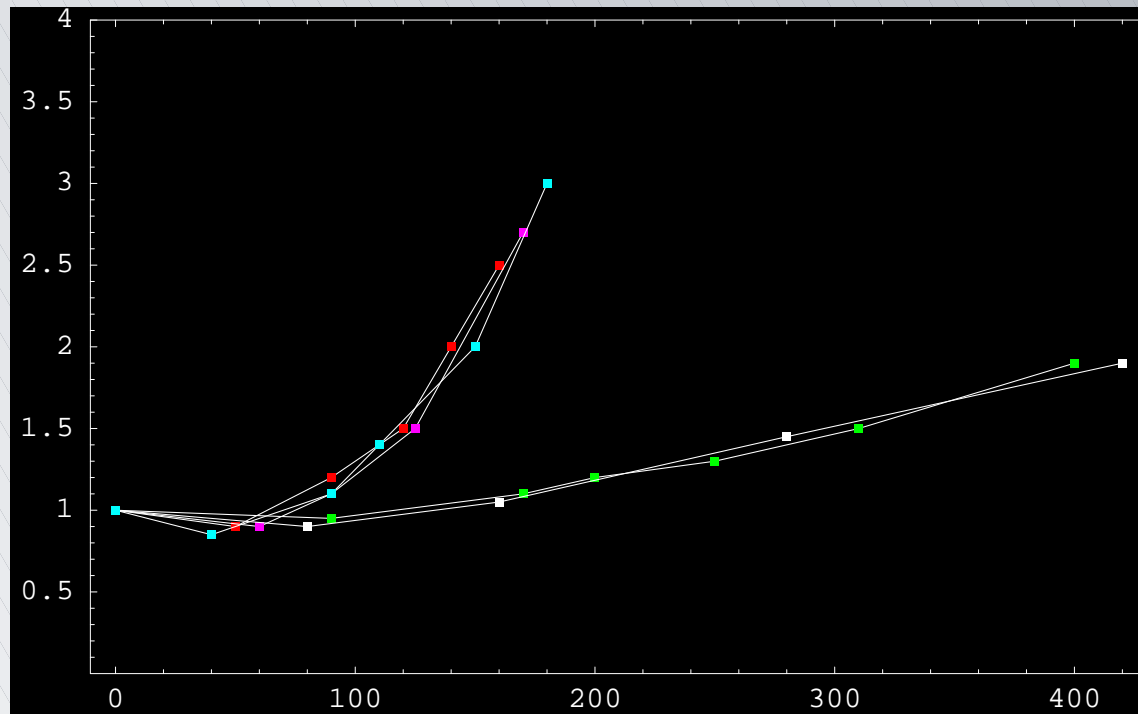
additive

Degradation
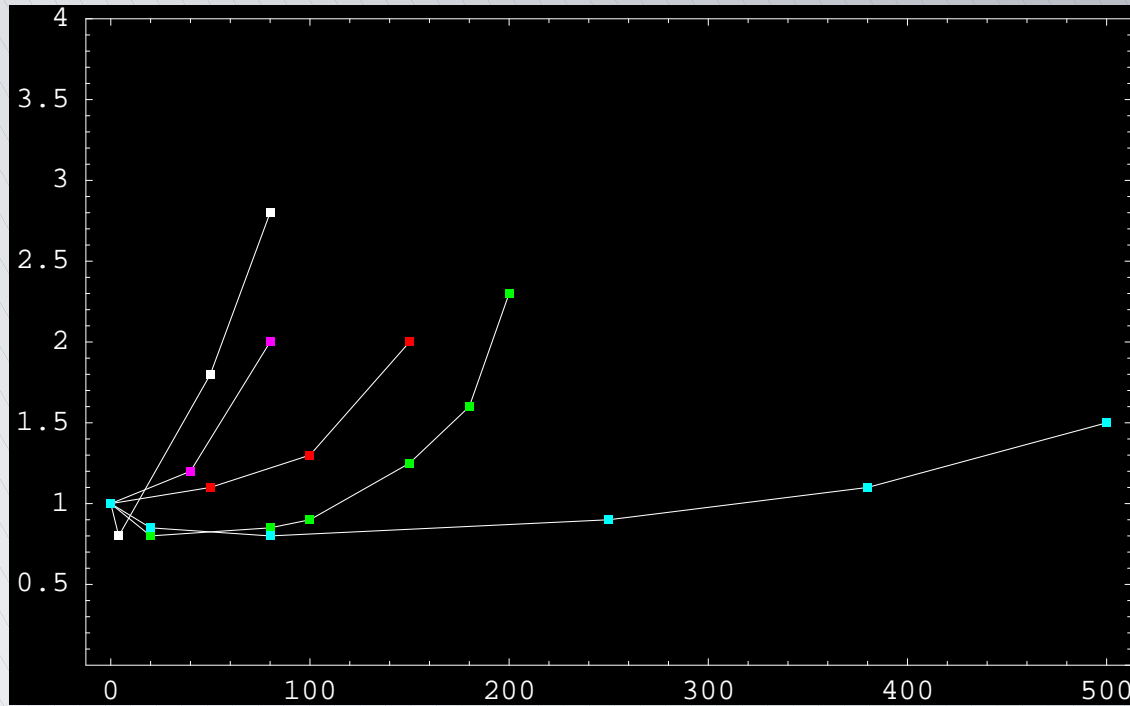
Relative apparent viscosity at $10\ s^{-1}$ vs. time for two different CWS at various shear rates.

The white and green marks identify a type of mixture (Colombian CWS) at two different shear rates ($20\ s^{-1}$ and $50\ s^{-1}$); the other marks identify another mixture (Russian CWS) at three different shear rates ($20\ s^{-1}$, $50\ s^{-1}$, and $80\ s^{-1}$)

Degradation

Relative apparent viscosity at $10\ s^{-1}$ vs. specific cumulative energy using the same data of the previous plot. All marks related to the same type of mixture arrange themselves on a unique curve *regardless of the operated shear rate*

Additive dynamics

Main variables: A % of additive available in water, B % of additive adsorbed by non–ionized sites on coal particles, Y concentration of ions adsorbed on coal particles, I concentration of ions in water, $\bar{B}$ maximum quantity of dispersant adsorbable on coal particles, D % of "inert" additive adsorbed on coal particles

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Main facts:

- Internal frictions cause the transition $B \to D$ and $I \to Y$.

- The transition $A \to B$ occurs to replace the dispersant becoming inert.

- While $A \to B$ is reversible, $I \to Y$ and $B \to D$ are not.

- Irreversible transitions are activated only by internal dissipation due to shear.

Additive dynamics

$$\dot{A} = -\mu_1 A(\bar{B} - B) + \mu_2 B \qquad (\mu_1, \mu_2 > 0 \quad \text{constants})$$

$$\dot{B} = \mu_1 A(\bar{B} - B) - \mu_2 B$$

$$\dot{D} = -\lambda Y D \qquad (\lambda > 0 \quad \text{constant})$$

$$\dot{Y} = \alpha_1(\bar{B} - B - Y)(I_0 - Y) - \alpha_2 Y \quad (\alpha_1, \alpha_2 > 0 \quad \text{constants})$$

$$\dot{\bar{B}} = f(W)(B_\infty - \bar{B})$$

with initial conditions $A(0) = A_0$, $B(0) = B_0$, $I(0) = I_0$, $f(W)$ function of the dissipated power and B_∞ asymptotic value of B. Constants μ_1, μ_2 are the rate of adsorption and desorption respectively. Clearly $I(t) + Y(t) = I_0$ and $A + B = D$.

Degradation in a pilot loop

Once B is determined, the CWS mixture can modeled as a *Bingham fluid* where the characteristic rheological parameters are functions of B.

Experimental data in a batch reactor fit very well the model (in this case all parameters depend only on time, not on spatial coordinates).

However in a pipeline the spatial dependence of rheological parameters cannot be neglected and the problem is much more complicated!

Degradation in a pilot loop

Quasi–steady approximation: the degradation time scale is much larger than the loop circulation time

Main variables in the axisymmetric geometry: $\tau(r,t)$ shear stress, η_B (constant) plastic viscosity, $\tau_0(r,t)$ yield stress, $v(r,t)$ velocity, r radius, $G(t)$ pressure gradient, $s(t)$ free surface

Degradation in a pilot loop

$$
\begin{aligned}
(\tau - \tau_0)_+ &= \eta_B |\partial_r v|, & r \in (0, R), t > 0 \\
G(t) &= (1/r)\partial_r(r\tau) & r \in (0, R), t > 0 \\
\partial_r v \mid_{r=s(t)} &= 0 & t > 0 \\
s(t) &= 2\tau_0(s(t), t)/G(t) & t > 0 \\
\partial_t \tau_0 &= \tau |\partial_r v|, & r \in (0, 1), t > 0
\end{aligned}
$$

Unexpected phenomena: the free boundary (separating the sheared and the unsheared regions) can touch the pipe wall or a new free boundary can grow on the wall and meet the original one in a finite time. Both cases lead to the blockage of the pipeline
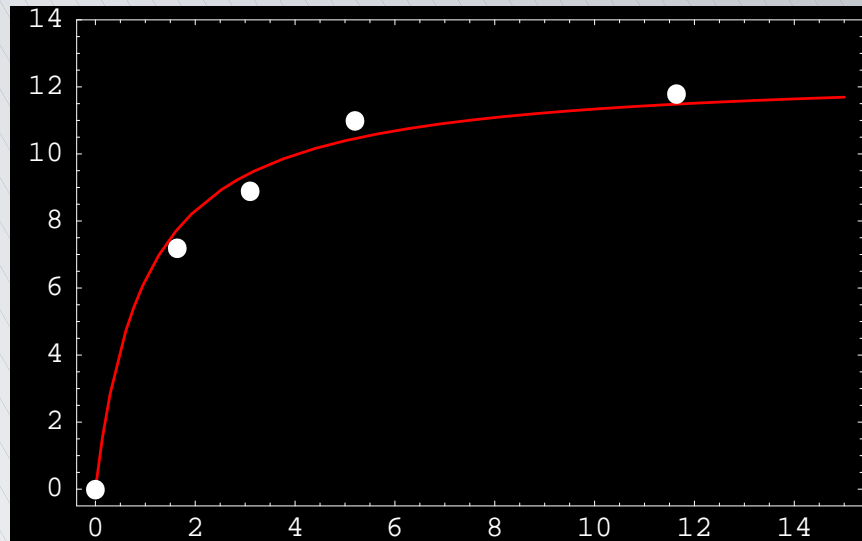
Sedimentation velocity

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Behaviour of the sedimentation coefficient α versus shear in a Bingham fluid. The proportionality coefficient of the "square radius"–law depends on the shear rate. Note that $v_0(0) = 0$!

Sedimentation dynamics in a pipe.

- Model variables: r pipe radial coordinate, x longitudinal axis of the pipe, t time, $\dot{\gamma}(r)$ (known function of τ, τ_0, η_B)

Sedimentation dynamics in a pipe.

🔴 Simplifying assumptions: the ratio "sediment thickness/pipe radius" is rather small, rheological parameters remain constant (the degradation time scale is much greater than the pipelining time), the sediment bed is partially transported away by the main flux, the geometry of the sediment cross–section is "essentially known", the mass flux of sediment per unit time $q(x, t)$ through a cross–section at distance x is a known function of $a(x, t)$, the area of the sediment cross–section at distance x and time t.

Sedimentation dynamics in a pipe

● **Consequences:** the total sediment rate $S_T(x)$ per unit length of the pipe at distance x from the origin can be explicitly evalutated as a function of the settling particle concentration and the convective velocity of the main flux

Sedimentation dynamics in a pipe.

- Evolution equation for $a(x, t)$

$$\frac{\partial a}{\partial t} + q'(a)\frac{\partial a}{\partial x} = S_T(x)$$

with the initial–boundary conditions $a(x, 0) = a(0, t) = 0$

Solutions

- best regime:

- attention regime:

Solutions

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- In all cases of physical interest the solution exists globally

Sedimentation bed profiles

PIPELINE

RIGID CORE

RIGID CORE

SEDIMENTATION BED

Δ

STATIC LAYER

DYNAMIC LAYER

SED. ZONE
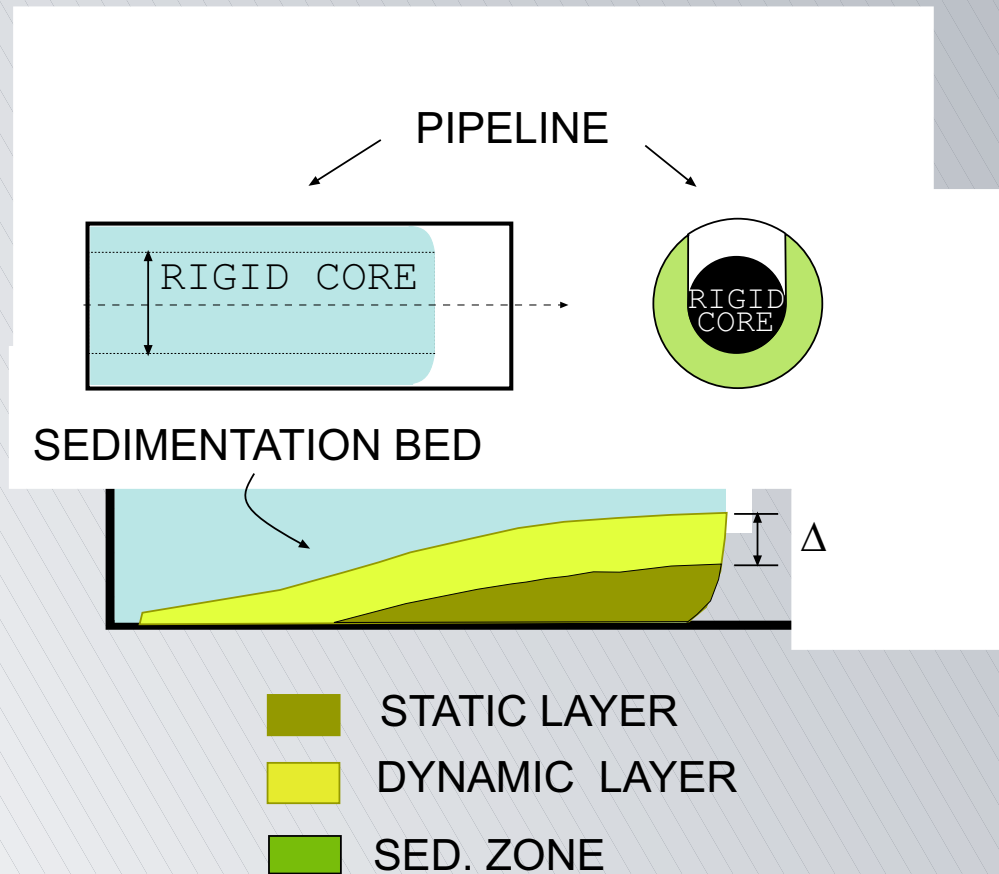
dynamics of the bed

Bed profile at various time: behind the maximum the bed remains stationary

Sedimentation bed profiles

Q (m^3/h)	100	150	250	450
Δ (cm)	0.7	1.0	1.8	3.2

Estimated values of Δ as a function of Q

Sedimentation bed profiles

$Q\ (m^3/h)$	$\Delta\ (cm)$	Gap (cm)	t_{cr} (days)	$x_{cr}\ (Km)$
100	0.7	3.5	0.4	0.48
150	1.0	4.2	0.5	1.24
250	1.8	5.4	∞	≥ 100
450	3.2	7.1	∞	≥ 100

Critical time and distances needed by the static sediment to reach 2% (=1cm) of the pipe diameter

Sedimentation bed profiles

$\Delta\ (cm)$	$t_{cr}\ (days)$	$x_{cr}\ (Km)$	$T_{cr}\ (days)$
1.4	0.71	3.57	1.01
1.5	0.97	4.99	1.35
1.6	1.51	7.5	2.08
1.7	3.20	14.2	3.85
1.8	∞	∞	∞
1.9	∞	∞	∞
2.0	∞	∞	∞

Critical times and distances: T_{cr} is the time needed by the system to reach a state in which the thickness of the static layer is above $h_{\mathrm{cr}} = 2R/100$ *over a longitudinal section of the pipe with length $\approx L/100$*

Sedimentation bed profiles

pipe radius $R = 25cm$, discharge $Q = 250 \ m^3/h$

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