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Rheology of ceramic suspensions

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Rheology is the science of deformation and flow. It is the part of continuum mechanics that investigates dependence of stress on deformation (strain) and deformation rate (strain rate). Based on the rheological classification triangle, all materials can be classified according to their rheological behavior, see Figure 1.

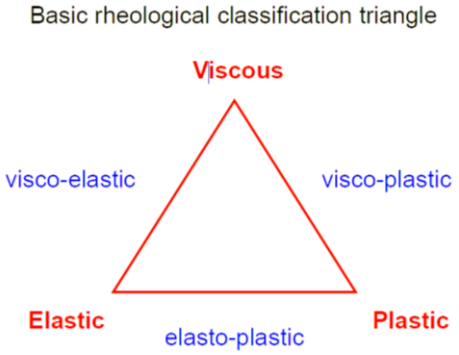

Fig.1: Rheological classification triangle [Pabst W., Uhlířová T.: Mechanics of Materials, e-learning presentations, UCT Prague 2018].

Viscous: gases, liquids, metal melts, suspensions …

Viscoplastic: ceramic pastes, clay, soil, granular materials …

Viscoelastic: polymer solutions, polymer melts …

The constitutive equation of purely viscous fluids is

$$\tau = \tau(\gamma)\,,$$

where τ is **shear stress** [Pa] and γ – gradient of velocity **(shear rate)** [s^{-1}],

$$\gamma = \frac{\partial v_x}{\partial y}\,.$$

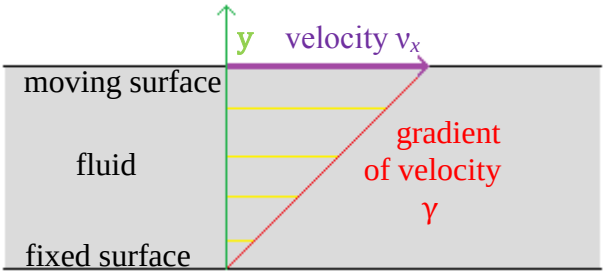

Fig.2: Couette flow geometry (schematic).

Linear case of 1D shear stresses: Newtonian fluids $\tau = \mu \cdot \gamma$, where μ = viscosity (coefficient of dynamic shear viscosity).

Nonlinear case of 1D shear stresses: Generalized Newtonian fluids $\tau = \eta(\gamma) \cdot \gamma$, where $\eta(\gamma)$ = apparent viscosity.

Power law (Ostwald de Waele model): $\boxed{\tau = \mathrm{K} \cdot \gamma^{\mathrm{n}}}$

Bingham model: $\boxed{\tau = \tau_0 + \mathrm{K} \cdot \gamma}$

Herschel-Bulkley model (generalized Bingham model): $\boxed{\tau = \tau_0 + \mathrm{K} \cdot \gamma^{\mathrm{n}}}$

τ_0 – yield stress
K – consistency coefficient
n – flow index; n > 1 pseudoplastic (shear thinning); n > 0 and n < 1 dilatant (shear thickening)

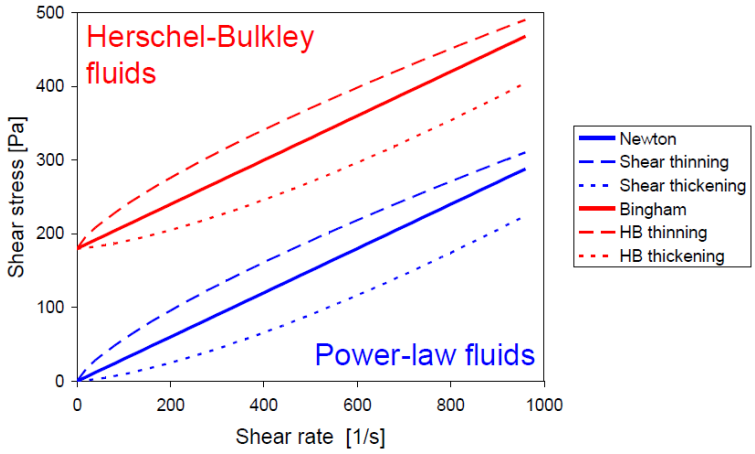

Fig.3: Basic types of non-Newtonian fluids [Pabst W., Uhlířová T.: Mechanics of Materials, e-learning presentations, UCT Prague 2018].

If the flow curve shows also time dependence, the system is not purely viscous and the viscosity should not be evaluated using constitutive equation for viscous fluids. Time-dependent shear thinning is called thixotropy (wall paints, cosmetic and pharmaceutical creams, etc.), time-dependent shear thickening is called rheopexy (less common, e.g. gypsum pastes and some printer inks).

Rheological behavior of dispersion is influenced by

- Viscosity of the medium
- Particle concentration
- Particle size
- Particle shape
- Interactions of particles with other particles or with the medium
- Temperature – viscosity decreases with increasing temperature

The effective viscosity of disperse systems is higher than that of the pure medium. Einstein's equation for a dilute disperse system with spherical, rigid and non-interacting particles is $\eta = \eta_0(1 + 2{,}5 \cdot \varphi)$, where φ is the volume fraction.
For generalized Newtonian fluids viscosity depends on shear rate, so either apparent viscosity or differential viscosity should be used with the information for which shear stress it was determined. Usually the apparent viscosity is preferred.

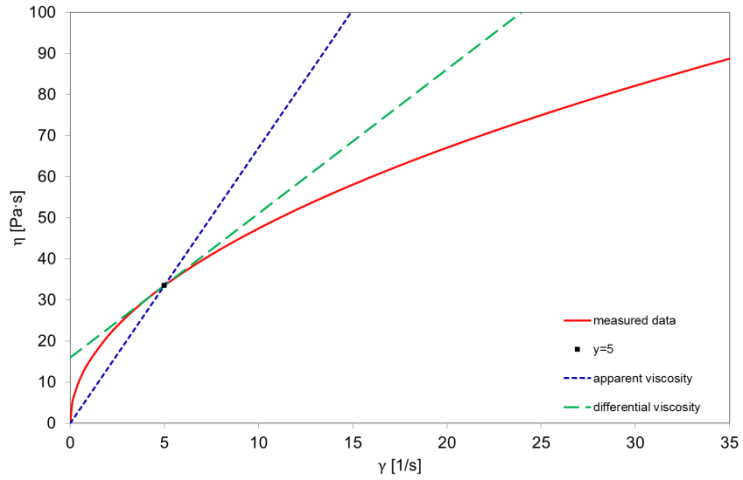

Fig.4: Overview of apparent and differential viscosities for γ_i = 5 s^{-1}.

Apparent viscosity – slope of the secant line for γ_i : $\eta(\gamma) = \left.\frac{\tau}{\gamma}\right|_{\gamma_i}$

Differential viscosity – slope of the tangent line for γ_i : $\eta(\gamma) = \left.\frac{d\tau}{d\gamma}\right|_{\gamma_i}$

Viscosity measurements

Capillary viscometer

Capillary viscometers are based on the measurement of volumetric flow of the fluid through a cylindical orifice (die) of defined dimensions. The shear stress is given by

$$\tau = \frac{D\Delta p}{4L}$$

and the shear rate (more precisely the apparent shear rate) is given by

$$\gamma = \frac{8\bar{v_z}}{D}$$

(Δp – pressure difference, $\bar{v_z}$ – mean velocity).

Höpplers's ball viscometer

The measurement is based on Stokes' relation for the fall of ball in viscous medium and viscosity is calculated from the settling velocity of the ball. This viscometer can be used (i.e. provides a correct viscosity) only for Newtonian fluids.

$$\eta = \frac{D^2(\rho_s - \rho_l)g}{18v}$$

Rotational viscometer

Rotational viscometers can have different geometrical arrangement, such as plate-plate or cone-plate, but the most appropriate and most frequently used system for low viscosity fluids is the arrangement of two concentric cylinders, between which there is narrow gap filled with the fluid to be measured. One of the cylinders is rotating with constant angular velocity. For suffiently narrow gaps Couette flow is approached in such system, which is a type of laminar flow of viscous fluid between two parallel surfaces (the curvature is neglected in this case), one moving and one static.

$$\tau = \frac{M}{2\pi R_1^2 h}$$

$$\gamma = \frac{\omega}{1 - (R_1/R_2)^2}$$

M – torque, ω – angular velocity

Workflow

The day before the work

1. preparation of kaolin suspensions – **schedule should be confirmed with lecturer by email, you have calculate the required amount of water and deflocculant beforehand**
   - 25 g kaolin
   - 25 ml water (total, the water contained in deflocculant should be included)
   - deflocculant – available as 5% water solution of tetrasodium pyrophosphate, its concentration will be set as 0.1, 0.2, 0.3, 0.5 and 1 wt.% in the suspension (related to the solid phase)
   - the alumina balls
2. overnight shaking on a laboratory shaker

The day of the work

3. short test
4. application of ultrasound pulses on suspensions
5. measurement of viscosity on rotational viscometer

The laboratory report will contain:

1. Introduction – short description of principle of measurement
2. Experimental – table with overview of prepared suspensions and description of measurement
3. Results and discussion – graph of viscosity dependency of suspensions on the deflocculant concentration and discussion of results
4. Conclusions

Recommended literature:

[1] Pabst W., Havrda J., Gregorová E.: Steps towards rational modelling of ceramic injection molding, *Ceramics–Silikáty* ***41*** *(2)*, 47–54 (1997).

[2] Pabst W., Havrda J., Gregorová E.: The capillary viscometer method for the rheological characterization of thermoplastic ceramic pastes, *Ceramics– Silikáty* ***42*** *(4)*, 177–185 (1998).

[3] Pabst W., Havrda J., Gregorová E.: Rheology of ceramic injection-molding feedstocks, *Ceramics–Silikáty* ***43*** *(1)*, 1–11 (1999).

[4] Pabst W.: Fundamental considerations on suspension rheology, *Ceramics-Silikáty* ***48*** *(1)*, 6–13 (2004).

[5] Pabst W., Uhlířová T.: Mechanics of Materials, e-learning presentations, UCT Prague 2018.