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Deriving a Process Viscosity for Complex Particulate Nanofibrillar Cellulose Gel-containing Suspensions

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Abstract:
Phase-separable particulate-containing gel structures constitute complex fluids. In many cases they may incorporate component concentration inhomogeneities within the ensemble matrix. When formulated into high consistency suspensions, these can lead to unpredictable time-dependent variations in rheological response, particularly under shear in simple parallel plate and cylindrical rotational geometries. Smoothing function algorithms are primarily designed to cope with random noise. In the case studied here, namely nanocellulose-based high consistency aqueous suspensions, the system is not randomised but based on a series of parallel and serial spatial and time related mechanisms. These include: phase separation, wall slip, stress relaxation, breakdown of elastic structure and inhomogeneous time-dependent and induced structure rebuild. When vacuum dewatering is applied to such a suspension while under shear, all these effects are accompanied by the development of an uneven solid content gradient within the sample, which further adds to transitional phenomena in the recorded rheological data due to spatial and temporal differences in yield stress distribution. Although these phenomena are strictly speaking not noise, it is nevertheless necessary to apply relevant data smoothing in order to extract apparent/process viscosity parameters in respect to averaging across the structural ensemble. The control parameters in the measurement of the rheological properties, to which smoothing is applied, are focused on parallel plate gap, surface geometry, shear rate, oscillation frequency and strain variation, and relaxation time between successive applications of strain. The smoothing algorithm follows the Tikhonov regularisation procedure.

Key words:
data smoothing, rheology of gel suspension, dewatering, immobilisation, nanocellulose, phase separable process

1 INTRODUCTION

Gel structures may exhibit very different rheological behaviour depending on the mechanism of gelation. For example, bridging structures between particles may undergo viscoelastic response to strain in respect to the flocculating mechanism [1, 2]. In some gels, for example those based on mineral nanoclay particles, the gelation may relate to a direct swelling of the particles due to intercalate exchange and exfoliation [3, 4]. Polymer gels, on the other hand develop a structural integrity due to liquid uptake potential and diffusion between the constituent polymer molecules in the matrix [5]. An example material which is undergoing intensive research currently is nanocellulose and nanofibrillar cellulose, derived from the refining and/or oxidation of tree fibres [6–9]. This highly charged hydrophilic material behaves similarly to a superabsorbing polymer, in that the nanoparticulate matter itself does not swell, but the attraction to water results in a high osmotic pressure leading to bound and interstitial water molecules clustered within a swollen gel [10, 11]. This behaviour, when introduced in mixes with other suspension particles, including, for example, micro and macroscopic cellulose fibres and inert pigment fillers, results in challenging rheological properties when considered for applications in a wide range of manufacturing processes, ranging from paper and board manufacture, as well as composites, to food, pharmaceuticals and cosmetics [12–16]. Such materials form phase-separable gel structures, which may incorporate inhomogeneities within the ensemble matrix when incorporated in high consistency suspensions, and so constitute complex fluids, whose rheological response can lead to unpredictable time-dependent variations under shear in simple parallel plate and cylindrical rotational geometries [17–19].

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REFERENCES

[1] Chen B, Lee S, Lee D: Rheological characteristics of the cationic polyelectrolyte flocculated wastewater sludge, Water Resources 18 (2005) 4429–4435.

[2] Seyssiecq I, Ferrasse J, Roche N: State-of-the-art: rheological characterisation of wastewater treatment sludge, Biochem. Eng. J. 14 (2003) 41–56.

[3] Santiago F, Mucientes E, Osorio M, Rivera C: Preparation of composites and nanocomposites based on bentonite and poly (sodium acrylate). Effect of amount of bentonite on the swelling behaviour, Euro. Polym. J. 43 (2007) 1–9.

[4] Gu Z, Song G, Liu W, Li P, Gao L, Li H, Hu X: Preparation and properties of styrene butadiene rubber/natural rubber/organo-bentonite nanocomposites prepared from latex dispersions, Appl. Clay. Sci. 3 (2009) 241–244.

[6] Lamminmäki T, Kettle J, Rautkoski H, Kokko A, Gane PAC: Limitations of current formulations when decreasing the coating layer thickness of papers for Inkjet printing, Ind. Eng. Chem. Res. 12 (2011) 7251–7263.

[7] Hubbe MA, Rojas OJ, Lucia LA, Sain M: Cellulosic nanocomposites: A review, BioResources 3 (2008) 929–980.

[8] Subramanian R, Hiltunen E, Gane PAC: Potential use of micro- and nanofibrillated cellulose composites exemplified by paper, cellulose fibers, bio- and nano-polymer composites, in Kalia S, Kaith BS, Kaur I (Eds.): Cellulose Fibers: Bio- and Nano-Polymer Composites, Chapter 5, Springer Verlag, Berlin (2011).

[9] Laine J, Österberg M, Delphine M, Pohjola L, Sinisalo I, Kosonen H: Method for producing furnish, furnish and paper, US Patent Application 13/318,246 (2010).

[10] Saito T, Isogai A: TEMPO-mediated oxidation of native cellulose, Appita Ann. Conf. 3 (2005) 337–340.

[11] Aouada FA, de Moura MR, Orts WJ, Mattoso LH: Preparation and characterization of novel micro- and nanocomposite hydrogels containing cellulosic fibrils, J. Agri. Food Chem. 17 (2011) 9433–9442.

[12] Klemm D, Schumann D, Kramer F, Heßler N, Koth D, Sultanova B: Nanocellulose materials – different cellulose, different functionality, Macromol. Sym. 280 (2009) 60–71.

[13] Hubbe MA, Panczyk M: Dewatering of refined, bleached hardwood kraftpulp by gravity, vacuum, and centrifugation with applied pressure, Part 2: Effects of wet-end additives, O Papel (Brazil) 68 (2007) 88–100.

[14] Pujara J, Siddiqui M, Liu Z, Bjegovic P, Takagaki S, Li P, Ramaswamy S: Method to characterize the air flow and water removal characteristics during vacuum dewatering, Part II: Analysis and characterization, Drying Technol. 26 (2008) 341–348.

[15] Dimic-Misic K, Puisto A, Gane PAC, Nieminen K, Alava M, Paltakari J, Maloney T: The role of MFC/NFC swelling in the rheological behaviour and dewatering of high consistency furnishes, Cellulose 6 (2013) 2847–2861.

[16] Kieweg SL, Katz DF: Squeezing flows of vaginal gel formulations relevant to microbicide drug delivery, J. Biomech. Eng. 128 (2006) 540–553.

[17] Dimic-Misic K, Puisto A, Paltakari J, Alava M, Maloney T: The influence of shear on the dewatering of high consistency nanofibrillated cellulose furnishes, Cellulose 20 (2003) 1853–2020.

[19] Illa X, Puisto A, Lehtinen A, Mohtaschemi M, Alava MJ: Transient shear banding in time-dependent fluids, Phys. Rev. E. 87 (2013) 022307.

[20] Ovarlez G, Rodts S, Chateau X, Coussot P: Phenomenology and physical origin of shear localization and shear banding in complex fluids, Rheol. Acta 48 (2009) 831–844.

[21] Yeow YL, Chandra D, Sardjono AA, Wijaya H, Leong Y, Khan A: A general method for obtaining shear stress and normal stress functions from parallel disk rheometry data, Rheol. Acta. 44 (2005) 270–277.

[22] Campbell GR, Leong Y, Yeow YL: Obtaining the shear stress shear rate relationship and yield stress of liquid foods from parallel disk data, J. Food Sci. 70 (2005) 50–55.

[23] Shih WY, Shih W, Aksay IA: Elastic and yield behaviour of strongly flocculated colloids, J. Am. Ceramic Soc. 82 (1999) 616–624.

[24] Ayol A, Dentel SK, Filibeli A: Rheological characterization of sludges during belt filtration dewatering using an immobilization cell, J. Environ. Eng. 9 (2010) 992–999.

[25] Fenistein D, van Hecke M: Kinematics: Wide shear zones in granular bulk flow, Nature 6955 (2003) 256–256.

[26] Yeow YL, Leong Y, Khan A: Error introduced by a popular method of processing parallel-disk viscometry data, Appl. Rheol. 17 (2007) 66415.

[27] Chang G-S, Koo J-S, Song K-W: Wall slip of vaseline in steady shear rheometry, Korea-Australia Rheol. J. 15 (2003) 55–61.

[28] Bertola V, Bertrand F, Tabuteau H, Bonn D, Coussot P: Wall slip and yielding in pasty materials, J. Rheol. 47 (2003) 1211–1226.

[29] Divoux T, Grenard V, Manneville S: Rheological hysteresis in soft glassy materials, Phys. Rev. Lett. 110 (2013) 018304.

[30] Puisto A, Illa X, Mohtaschemi M, Alava M: Modeling the rheology of nanocellulose suspensions, Nordic Pulp Paper J. 27 (2012) 277–281.

[31] Van Hecke M: Granular matter: A tale of tails, Nature 7045 (2005) 1041–1042.

[32] Jäder J, Järnström L, Engström G: The immobilization cell revisited: Prediction of dewatering kinetics and immobilised layer properties for coating colours, Nordic Pulp Paper J. 18 (2003) 382–387.

[33] Pajari H, Koskela H: Consolidation of coating colors – Experimental studies, 11th Advanced Coating Fundamentals Symposium Proceedings: The Latest Advances in Coating Research and Development (2010) 347–359.

[34] Dimic-Misic K, Gane PAC, Paltakari J: Micro-and Nanofibrillated cellulose as rheology modifier additive in CMC-containing pigment coating formulations, Ind. Eng. Chem. Res. 52 (2013) 16055–16083.

[35] Iotti M, Gregersen ØW, Moe S, Lenes M: Rheological studies of microfibrillar cellulose water dispersions, J. Polym. Environ. 19(2011) 137–145.

[36] Saarikoski E, Saarinen T, Salmela J: Flocculated flow of microfibrillated cellulose water suspensions: an imaging approach for characterisation of rheological behaviour, Cellulose 19 (2012) 647–659.

[37] Lasseuguette E, Roux D, Nishiyama Y: Rheological properties of microfibrillar suspension of TEMPO-oxidized pulp, Cellulose 15 (2008) 425–433.

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[38] Møller PCF, Mewis J, Bonn D: Yield stress and thixotropy: On the difficulty of measuring yield stresses in practice, Soft Matter 2 (2006) 283–283.
[39] Willenbacher N, Hanciogullari H, Rädle M: New laboratory test to characterize immobilization and dewatering of paper coating colors, Tappi J. 82 (1999) 167–174.
[40] Besseling R, Isa L, Ballesta P, Petekidis G, Cates M, Poon W: Shear banding and flow-concentration coupling in colloidal glasses, Phys. Rev. Lett. 105 (2010) 268301.
[41] Walls HJ, Caines SB, Sanchez AM, Khan SA: Yield stress and wall slip phenomena in colloidal silica gels, J. Rheol. 4 (2003) 847–868.
[42] Pal R: Slippage during the flow of emulsions in rheometers, Colloids Surf. A: Physicochem. Eng. Aspects 162 (2000) 55–66.
[43] Sato ACK, Perrechil FA, Cunha RL: Rheological behavior of suspensions dispersed in non-Newtonian matrix, Appl. Rheol. 23 (2013) 45297.
[44] Sadati M, Luap C, Kröger M, Gusev A, Öttingen HC: Smooth full field reconstruction of velocity and its gradients from noisy scattered velocimetry data in a cross-slot flow, J. Rheol. 55 (2011) 353–376.
[45] Takeh A, Shanbhag S: A computer program to extract the continuous and discrete relaxation spectra from dynamic viscoelastic measurements, Appl. Rheol. 23 (2013) 24628.
[46] Wollny K: New rheological test method to determine the dewatering kinetics of suspensions, Appl. Rheol. 11 (2001) 197–202.
[47] Richmond F, Co A, Bousfield D: The coating of nanofibrillated cellulose onto paper using flooded and metered size press methods, 2012 PaperCon Conference TAPPI (2012) 18.
[48] Su J, Mosse WK, Sharman S, Batchelor W J, Garnier G: Effect of tethered and free microfibrillated cellulose (MFC) on the properties of paper composites, Cellulose 20 (2013) 1925–1935.
[49] Yeow YL, Leong Y, Khan A: Non-Newtonian flow in parallel-disk viscometers in the presence of wall slip, J. Non-Newtonian Fluid Mech. 139 (2006) 85–92.
[50] Jäder J, Järnström L: The influence of thickener addition on filter cake formation during dewatering of mineral suspensions, Appl. Rheol. 13 (2003) 125–131.
[51] Puisto A, Illa X, Mohtaschemi M, Alava M: Modeling the viscosity and aggregation of suspensions of highly anisotropic nanoparticles, Euro. Phys. J. E 35 (2012) 1–7.
[52] Tikhonov AN: Equations of mathematical physics, Dover Publications (1963).
[53] Karppinen A, Vesterinen AH, Saarinen T, Pietikäinen P: Effect of cationic polymethacrylates on the rheology and flocculation of microfibrillated cellulose, Cellulose 18 (2011) 1381–1390.
[54] Barnes H, Carnali J: The vane-in-cup as a novel rheometer geometry for shear thinning and thixotropic materials, J. Rheol. 34 (1990) 841–866.
[55] Chinga-Carrasco G, Kuznetsova N, Garaeva M, Leirset I, Galiullina G, Kostochko A, Syverud K: Bleached and unbleached MFC nanobarriers: properties and hydrophobisation with hexamethyldisilazane, J. Nanopart. Res. 14 (2012) 1280–1290.
[56] Dimic-Misic K, Salo T, Paltakari J, Gane PAC: Balancing the Rheological Properties of Nanofibrillar Cellulose-formulated Pigment Coating Colours, Nordic Pulp Paper J. 29 (2014) 253-270.
[57] Willenbacher N: Novel approaches to explain the rheological properties of colloidal structures, Current Opinion Colloid Interf. Sci. 16 (2011) 1–2.
[58] Jäder J, Järnström L, Engström G: The immobilization cell revisited: Prediction of dewatering kinetics and immobilised layer properties for coating colours, Nordic Pulp Paper J. 18 (2003) 382–387.
[59] Landman KA, White LR, Eberl M: Pressure filtration of flocculated suspensions, AIChE Journal 41 (1995) 1687–1700.
[60] Mezger TG: The rheology handbook: For users of rotational and oscillatory rheometers, Vincentz, Hannover (2006).
[61] Press WH, Flannery BP, Teukolsky SA, Vetterling WT: Numerical Recipes in FORTRAN 77: The Art of Scientific Computing, Cambridge University Press, Cambridge (1992).
[62] Engl HW, Hanke M, Neubauer A: Regularization of inverse problems, Springer, Berlin (1996).

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