Off-state viscosity and yield stress optimization of magneto-rheological fluids: a mixture design of experiments approach

Antonio J. F. Bombard*, Rafael F. Ierardi,
Pedro P. Balestrassi, Anderson P. Paiva

Federal University at Itajubá
Av. BPS 1303, Itajubá/MG – 37.500-903, Brazil, phone: +55-35-3629-1222; fax: +55-35-3629-1140,
** Corresponding author: bombard@unifei.edu.br*

Magneto-Rheological Fluids (MRFs) are composite or multiphase materials. They are commonly prepared with some ferromagnetic phase dispersed in a chemically inert, non-volatile liquid. Typical materials include iron powders and mineral, silicone or synthetic oils. MRFs have the ability to change their rheological properties. When a magnetic field is applied, MRFs can change from a fluid to a near solid in a reversible way – with a relatively fast time of response (~10 milliseconds). The rheological properties are controlled by the field strength, which makes MRFs very promising for several technological devices, especially in mechatronics.

The magneto-rheological effect increases with the volume fraction of iron powder that is the active phase. However, one of the challenges in formulating good MRFs is to keep the so-called *off state* viscosity – the viscosity without magnetic field – as low as possible. Since the earlier works of *Mooney* [1], *Krieger-Dougherty* [2], *Thomas* [3], and *Frankel and Acrivos* [4] it is well established that the relative viscosity of any suspension increases exponentially with the volume fraction.

It is also well-known that mix powders with different particle sizes and/or size distribution can be advantageous. Chemical and food engineering processes, powder metallurgy and ceramics industries, etc. have used this approach with success [5]. *Farris* reported that there is substantial reduction on the relative viscosity in multimodal suspensions – when compared to unimodal suspensions – if the total volumetric fraction Φ is above 55% v/v and depending on the volume fraction of large particles (Φ_L/Φ) [6].

To increase the maximum packing volume fraction and to reduce the viscosity for powders of uniform spheres with different size ratios, optimum blend ratio of binary, ternary, quaternary or quinary mixtures was well established by *Lee* [7]. Besides, *Dinger and Funk* [8] – based on the seminal work of *Andreasen and Andersen* [9] – have shown that it is possible to reduce the viscosity of powder dispersions with mixtures. This, however, requires mixing at least two decades of particle size. Three or more decades are often used. The ideally infinite number of decades is obviously impossible. In such way the gross particles are the main components, and the amount of other components decreases with the size reduction.

For powders with log-normal size distribution and mixing less than one size decade, the above mentioned approach does not work. More recently, *He and Ekere*, through computer simulation, have suggested that for concentrated suspensions of non-colloidal particles with log-normal distribution, the viscosity decreases as the standard deviation of the particle diameters increases [10].

It is also well-known that to maximize "on-state" force of MRF, bimodal particle distribution is better than unimodal [11,12]. On the other hand, according *Carlson* [13], large particles are the choice to minimize "off-state" forces.

The purpose of this paper is to optimize the blend ratio of ternary mixtures of spherical iron powders with different modes to get the minimum "off-state" viscosity as well as to maximize the yield stress under field in Magnetorheological Fluids. The Mixture Design of Experiments methodology [14] was here utilized considering the powders ‘A’ (coarse); ‘B’ (medium); and ‘C’ (fine) as mixture components and the viscosity and yield stress as mixture responses. The minimum viscosity was found close to the A-C triangle edge of a response surface diagram. On the other hand, the maximum yield stress was on the B-C edge. Figure 1 shows the mixture contour plot for the mean viscosity of the ternary blend. It can be seen that there is a region (arrow) where the “off-state” viscosity is minimized.

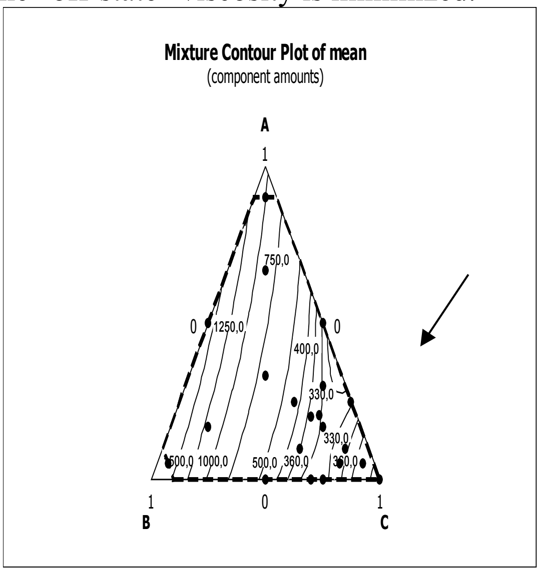

Fig. 1 Contour plot of the mean viscosity for the ternary mixture A-B-C.

The results show the power and robustness of DOE methodology to optimize and to tailor MRF performance, according to the desired application.

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References

[1] Mooney M (1951) “The Viscosity of a Concentrated Suspension of Spherical Particles”; Journal of Colloid Science 6(2):162 – 170.

[2] Krieger IM, Dougherty TJ (1959) “A Mechanism for Non-Newtonian Flow in Suspensions of Rigid Spheres” Transactions of the Society of Rheology 3: 137-152.

[3] Thomas DG (1965) “Transport Characteristics of Suspension .8. A Note on Viscosity of Newtonian Suspensions of Uniform Spherical Particles”; Journal of Colloid Science 20(3): 267.

[4] Frankel NA, Acrivos A (1967) “On Viscosity of a Concentrated Suspension of Solid Spheres”; Chemical Engineering Science 22(6): 847.

[5] German RM, “Particle Packing Characteristics”; Metal Powder Industries Federation; Princeton, 1989.

[6] Farris RJ (1968) “Prediction of the Viscosity of Multimodal Suspensions from Unimodal Viscosity Data”; Trans. Soc. Rheol.; 12(2): 281 – 301.

[7] Lee DI (1970) “Packing of spheres and its effect on the viscosity of suspensions”; J. Paint Technology 42: 579 – 587.

[8] Funk JE, Dinger DR (1993) “Predictive Process Control of Crowded Particulate Suspensions: Applied to Ceramic Manufacturing”, Kluwer Academic Pub., Norwel, USA.

[9] Andreasen AHM, Andersen J (1930) “Ueber die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten)”, Koll. Zeitschr. 50(3): 217 – 228.

[10] He D, Ekere NN (2001) “Structure simulation of concentrated suspensions of hard spherical particles” – AIChE Journal 47: 53 – 59.

[11] Foister RT, “Magnetorheological fluids”, US Patent 5,667,715 – Sep. 16, 1997.

[12] Weiss KD, Carlson JD and Nixon DA, “Method and MRF formulations for increasing the output of a MRF”, US Patent 6,027,664 – Feb. 22, 2000.

[13] Carlson JD; “MR Fluids and Devices in the Real World”; Oral presentation during ERMR 2004; Beijing, China.

[14] Cornell J (2002), “Experiments with Mixtures: Designs, Models, and the Analysis of Mixture Data” – 3rd edition, Wiley, New York.