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Determination of ferrosilicon medium rheology and stability

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ABSTRACT

Ferrosilicon (FeSi) has a fast settling rate in dense suspension, attributed to its very high solids density, coarse particle size, more spherical particle shape and low medium viscosity. The fast-settling nature in dense suspension is a challenge to acquire reliable rheological data. A testing rig was set up to maintain a constant medium density during the rheology measurement by circulating the medium to keep FeSi particles well suspended. A rotational rheometer with a modified concentric bob-cup measuring system was incorporated in the testing rig. Taylor number (T_a) was calculated and a threshold $T_a = 41.3$ was used to identify the onset of unstable laminar flow owning to the Taylor vortices and turbulence formation in the measuring system. The data with $T_a > 41.3$ were excluded in the determination of rheological flow curves. Evaluation of the modified measuring system with Newtonian silicone oils of known viscosities confirmed that the system can produce true flow curves over the entire tested shear rate range for a stable laminar flow ($T_a < 41.3$). This data reduction procedure was applied to the FeSi medium rheology measurement. It demonstrates that FeSi medium exhibits a pseudoplastic trend with a yield stress. The apparent viscosities were calculated at two shear rates, 10 s^{-1} that is assumed to be a typical shear rate in dense medium bath separators and 75 s^{-1} for dense medium cyclones. A characteristic curve between apparent viscosity and medium density was established, which can be used in FeSi selection for dense medium separation. Medium stability was determined from the FeSi sedimentation rate measurement. It shows that medium stability was closely correlated with medium viscosity. A trade-off between stability and viscosity for optimal dense medium separation should be established.

1. Introduction

In dense medium separation, medium rheology plays an important role in separation efficiency. A high viscosity increases particle misplacement in dense medium cyclones and baths. It decreases the separation density in cyclones due to a reduction in the medium differential. Collins et al. (1974), Napier-Munn (1990), Wood (1990) and He and Laskowski (1994) reported a reduction in dense medium cyclone efficiency at high feed medium densities, which was attributed to increased viscosity and increased medium segregation near the apex zone. Stoessner (1987) observed that the fine magnetite does not perform as well as coarse commercial magnetite in dense medium cyclones. As particle fineness is one of the factors affecting medium viscosity, Stoessner argued that the observation was attributed to the increased medium viscosity. Davis and Napier-Munn (1987) showed that cyclone separation efficiency was significantly reduced due to an increased medium viscosity caused by the clay contamination. Medium viscosity can change the separation density of bath separators as well, but it can lead to either increasing or decreasing separation density, depending on the bath feeding location.

Medium stability is another operational parameter influencing dense medium separation efficiency. All dense media solids are inherently unstable because they have a higher density than the liquid (water) in which they are suspended. Stability is important in determining the behaviour of the medium in the separator. In general it is desirable to have a stable medium to prevent strong density gradients in the separator, which usually inhibits an efficient separation. The appearance of density gradients due to flow reversals and turbulence fluctuations in the cyclone leads to the misplacement of feed particles, hence the reduction of separation efficiency. He and Laskowski (1994) observed that the separation efficiency and cut point shift for coarse particles (>2 mm) in a dense medium cyclone were mainly determined by the medium stability. Davis (1987) and Wood (1990) reported that a higher density differential led to a longer retention time of near-density materials in dense medium cyclone in both coal washing plant trials and pilot scale tests. The cyclone became unstable and periodically overloaded, resulting in a breakdown of the stable flow pattern and surging.

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In a review of the effects of dense medium viscosity on separation efficiency, Napier-Munn (1990) reported that very few studies have been undertaken on the direct effects of the rheological properties of the medium on the separation process. This is probably because of the experimental difficulties involved in the measurement of rheology in the process environment, and the problems of decoupling rheology from the other process variables.

In the past decades, much effort has been devoted to attempting to address the rheology measurement, modelling and application in mineral and coal processing research programs conducted at the Julius Kruttschnitt Mineral Research Centre (JKMRC). This includes the work of Baguley (1988), Castro (1990), Masinja (1992), Napier-Munn et al. (1994), Shi (1995), Dunglison and Napier-Munn (1995), Shi and Napier-Munn (1996a,b, 1999, 2002), Shi and Zheng (2003), Li et al. (2015), etc. One major development was to set up a testing rig at the JKMRC pilot plant for viscosity measurement of slurries containing fast-settling particles such as coarse minerals and ferrosilicon (FeSi) powders.

FeSi powders have wide applications in dense medium separation, particularly for the mineral and coal industries. In order to provide the rheological characteristic data and medium stability information to the FeSi users, the JKMRC was commissioned by DMS Powders, the major FeSi supplier, to conduct measurements of a number of FeSi samples to determine rheological property and stability. This paper presents the challenges in FeSi rheology measurement and the technical approaches to resolve the issues to acquire true rheological flow curves and medium stabilities of the FeSi samples.

2. The challenges in FeSi rheology measurement

2.1. FeSi material

There are two main FeSi product groups in the market, which are defined in terms of the manufacturing process: milled and atomised. They have similar chemical compositions. Quartz and steel scrap are melted in a submerged arc furnace with a reductant to produce molten ferrosilicon with a silicon content around 15%. The material is then water granulated, subsequently dried, milled and air classified into the various milled FeSi grades. The atomised FeSi with 14–16% silicon is manufactured by diluting 75% ferrosilicon with steel billets in an induction furnace. The molten alloy goes through high-pressure water atomisation, dried, and screen classified to produce the various grades of atomised FeSi products.

The difference between the milled and atomised FeSi products is in the particle shape. The particle shape of atomised FeSi is more spherical, and the milled FeSi is more angular. As a result, the atomised FeSi can produce high medium densities combined with low viscosities. In each product group, on the other hand, the difference in FeSi grade is in their size distributions. For example, the product fineness of the milled grades is in the order: 270D > 150D > 100D > 65D. The difference in particle size distributions affects both medium rheology and stability significantly, particularly at a high medium density.

DMS Powders supplied a number of FeSi samples for testing. FeSi 150D is one of them, which will be used as an example to demonstrate its rheology and stability characterisation.

2.2. The challenges

For dense medium separation, magnetite and FeSi are often used as dense media for the coal and mineral industries. Klein et al. (1995) found from a magnetite suspension in a laboratory column that there exhibited four distinct zones: At the top of the column, a supernatant forms, extending vertically to the position of the smallest settling particle that was originally at the top of the column. Below this position is the transition zone, which is characterised by increasing particle size and solids content with depth. The transition zone diminishes in size as the suspension solid content increases such that at a very high solid content it does not exist. Below the transition region is the constant density zone, which has a solid content and particle size distribution approximately equal to that of the original suspension. Immediately below this zone is the consolidation zone in which the settling particles form a sediment. A device consisting of a specially designed cup and bob system that attaches to a concentric cylinder rheometer was constructed to measure the rheological properties of magnetite suspensions in the constant density zone. Detailed information on the rheometer design, measuring errors, settling properties of the media, rheometer calibration with oils, shear rate calculations, and wall slip issues is presented in Klein et al. (1995).

The work to take magnetite dense medium rheology measurement in the constant density zone is perhaps one of the simplest and effective methods in dealing with concentrated dense medium. It requires a small amount of medium sample (350 ml to fill the constructed measuring system) for the rheological measurement, and the method is easy to implement. Of course its application is limited to the suspensions that exhibit suitable zone settling properties such as the magnetite dense media.

For FeSi dense medium suspensions it is doubted if the method using the zone settling properties can be applied to determine FeSi rheological properties, due to the fast-settling feature of the FeSi particles. The major differences between the magnetite and FeSi are in their solids densities, particle size, particle shape and medium viscosity:

- FeSi media is much heavier than the magnetite. The relative density (RD) of the magnetite used in Klein et al. (1995) work was 4.88, while that of the milled FeSi samples varies from 6.9 to 7.1, and the atomised FeSi can go up to 7.3.
- FeSi media is much coarser than the magnetite tested. The magnetite sample contains 90% passing 45 μm fines, while FeSi 150D only has 22% passing 45 μm.
- FeSi particles, the atomised FeSi in particular, have a more spherical shape than the mechanically milled magnetite dense media.
- At the same medium density in a unit of $kg\ m^{-3}$, FeSi medium has a smaller viscosity than the magnetite, attributable to the smaller solid volume concentration (due to the greater solids RD), the coarser particle size with less fines, and the more spherical shape.

Since particle settling velocity is positively correlated with the differential density (solid RD less medium RD) and particle size (in terms of d^2 where d is particle diameter), and inversely proportional to medium viscosity, FeSi media have a much faster settling rate than the magnetite, owing to the aforementioned differences in the inherent material properties of FeSi (the greater solid RD, coarser particle size d, and smaller medium viscosity). By way of example, the magnetite has a settling rate of $1.36\ cm\ min^{-1}$ in the interface of transition zone – constant density zone for a volume solids fraction of 0.15 (i.e. a medium density of $1582\ kg\ m^{-3}$) (Klein et al., 1995). To compare the settling rate at the same medium density, the measured FeSi 150D settling rates at various medium densities presented in Section 4.2 were regressed. The regression equation was used to estimate the settling rate of FeSi 150D particles at a medium density of $1582\ kg\ m^{-3}$. The estimated settling rate for FeSi 150D particles is $10.9\ cm\ min^{-1}$, which is 8 times as fast as the magnetite ($1.36\ cm\ min^{-1}$). Note that the other grades of FeSi samples (100D, 65D, etc.) have even faster settling rates than the 150D.