Rheological characterization of the solids phase in bio-industry disc-stack centrifuges is considered. Three discriminatory properties of the solids phase are investigated, namely, the particle settling velocity, the angle of repose, and the solids phase viscosity. The solids phase produced in disc-stack centrifuges in the food or biopharmaceutical industry possesses both liquid-like and solid-like properties which can be quantified by means of these test methods. The resulting rheological characterization can be used for diagnostic purposes in the selection process of industrial centrifuges and for optimization of centrifuge solids handling in biomass processing of suspension systems.

Keywords: Angle of repose, Biomass processing, Centrifuge solids rheology, Solids phase viscosity, Squeeze flow

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1 Introduction

1.1 General Remarks

The rheology of the solids phase is an important aspect in designing and controlling solid-liquid separation operations in industrial biomass processing. In fact, a wide range of solid phase materials in industrial applications share several common rheological features which enables the use of similar rheological probing methods. This applies to soft materials including cells, pastes, polymer networks, and flocculated suspensions. A review of recent rheological measurement techniques and challenges with applying them for these soft materials is given by Chen [1].

Two physical properties of the solids phase subjected to compression by earth gravity or by a magnified centrifugal force field are of fundamental importance: the mechanical strength of the solids network and the rate and to which degree liquid can be drained off the solids network during compression, i.e., the permeability of the solids network to the flow of the liquid phase. Two parameters describing these features of the solids network in theoretical modeling of the behavior of sedimentation of suspensions are the compressive yield stress and the hindered settling factor [2].

De Kretser et al. [3] provide a comprehensive overview of engineering areas involving compression of the solids phase in liquid-solid systems, including industrial dewatering in minerals processing, civil engineering, and geotechnical applications. Examples from filtration, centrifugation, and gravity thickening technologies are considered. De Kretser et al. [3] list a number of rheological parameters of the solids network used in these different research fields and show that in many cases these are related. Also, experimental techniques how to determine these parameters are discussed.

An applied approach is adopted in this work with focus on the impact of the solids phase rheology in the framework of disc-stack centrifuge technology development and optimization.

1.2 An Introductory Centrifugal Experiment

The sediment from an organic biomass material is for a certain period of time subjected to high compressional forces in a metal test tube by centrifugation in a bench top laboratory centrifuge. The centrifugal acceleration is 12 000 times stronger than the gravitational acceleration $g = 9.82 \text{ m s}^{-2}$, at the bottom of the sediment. After centrifugation the liquid supernatant is removed. Next, on top of the remaining sediment phase, a plastic, cylindrical piston with mass $m_0$ is positioned (Fig. 1). The sediment-piston system is now subjected to centrifugation for a period of time at 12 000g. The sediment is thereby exposed, besides compression, to shearing forces during centrifugation due to the movement of the piston cylinder displacing the sediment material in the direction opposite to the centrifugal force.

1) List of symbols at the end of the paper.
The piston penetration depth is recorded. This procedure is repeated using additional weights placed onto the piston, thereby increasing the centrifugal force. The experiment is repeated for three kinds of biomass material consisting of flocculated suspensions. The result of the experiment is presented in Fig. 1 with a plot of the piston penetration depth versus the applied piston mass load. The behavior of the sediments varies as a large variation in penetration depth is found. In the first experiment, sediment 1, the biomaterial remains intact and resists the shearing motion of the piston, even at higher loads. In the second and third experiments, with sediment 2 and 3, respectively, the sediment is sheared and transported in a direction opposite to the centrifugal force. In experiment 3, the displacement is twice as large as for sediment 2 at the same compressing and shearing loads. In both cases the penetration depth increases linearly with the cylinder mass load.

This simple experiment mimics the conditions prevailing in the solids phase in a disc-stack centrifuge and reveals the fact that the solids phase of the suspension can exhibit both liquid- and solids-like properties.

2 Theoretical Considerations – Continuous Solids Flow in Disc-Stack Centrifuges for Biomass Processing

A schematic picture of a continuous separation process of a biomass suspension in a disc-stack centrifuge is illustrated in Fig. 2.

The feed stream is entering the centrifuge with a volumetric flow rate \( Q_f \) and a volume concentration of solids in the feed stream, \( c_f \). The effluent and solids streams are leaving the centrifuge at volumetric flow rates \( Q_e \) and \( Q_s \) containing solids volume fractions \( c_e \) and \( c_s \), respectively. Continuity of the solids phase through the machine reads:

\[
 c_f Q_f = c_s Q_s \tag{1}
\]

assuming complete separation of the solids in the disc-stack centrifuge, i.e., \( c_e = 0 \). The capacity flow rate \( Q_c \) of the disc-stack centrifuge can be estimated using the equivalent settling area, \( \Sigma \), and the settling velocity \( v_s \), such that the clarification capacity of the centrifuge is limited by:

\[
 Q_c < v_s \Sigma \tag{2}
\]

The equivalent settling area of a disc-stack centrifuge, \( \Sigma \), can be expressed as [4]:

\[
 \Sigma = \frac{2 \pi n \omega^2 (r_2^3 - r_1^3) FL}{3 g \tan \theta} \tag{3}
\]

where \( n \) is the number of discs, \( \theta \) is the half disc angle, \( r_1 \) and \( r_2 \) are the respective inner and outer radii of the discs, \( \omega \) is the angular rotation frequency of the disc-stack centrifuge, and \( FL \) is a correction factor taking into account the number and width of the caulks on a disc.

Further,

\[
 v_s = \frac{\Delta \rho d^2 g}{18 \mu} \tag{4}
\]

is the Stokes settling velocity of a single solids particle in the gravitational force field of \( 1 g = 9.82 \text{ m s}^{-2} \). Here, \( d \) is the particle diameter, \( \Delta \rho \) is the difference in density between the solids particle and the suspension liquid phase, and \( \mu \) is the Newtonian, dynamic viscosity of the liquid phase.

Consider a solid biomass particle at radius \( r \) outside of the disc-stack (Fig. 2). The radial settling velocity of this particle relative to the liquid velocity in the rotating system is \( v_g G \), where

\[
 G = \frac{\omega^2 r}{g} \tag{5}
\]
is the centrifugal acceleration factor at radius \( r \), which is several orders of magnitude larger than the earth gravity \( g \), and thus the vertical gravity vector can be neglected.

In order to balance the particle settling velocity, \( v_g \), the solids stream bulk velocity \( U \), at the centrifuge outlet must be larger than \( v_g \) to enable a continuous discharge of the solids stream out from the centrifuge and, also, in order to avoid blockage of the flow due to accumulation of solids in the centrifuge outlet following to too quick a particle sedimentation rate.

Therefore, the solids discharge flow rate, \( Q_s \), must not be lower than \( v_g G A_s \), where \( A_s \) denotes the cross-sectional area of the solids duct outlet in the disc-stack centrifuge, in order to allow for continuous solids flow operation. From this it can be deduced that there exists a lower as well as an upper limit of \( Q_s \) since the feed stream capacity is limited according to the sigma theory (Eq. (2)). Using Eqs. (1) and (2), these restrictions on \( Q_s \) can be expressed as:

\[
v_g G A_s < Q_s < v_g \sum \frac{C_i}{c_i}
\]  

Eq. (6) provides an estimate of the range in the solids flow capacity of the disc-stack centrifuge to maintain continuous solids flow, within an order of magnitude, and highlights the importance of the solids settling velocity, \( v_g \), in terms of solids capacity of the centrifuge. It should be noted that \( v_g \) for clarification capacity corresponds to the smallest limiting particle while \( v_g \) for the largest limiting particle sets the limit for the solids stream.

The relative centrifugal acceleration \( G \) in the region outside of the disc-stack is typically in the range of 5000-15 000 \( g \) (\( = 49100-147300 \text{ m s}^{-2} \)) for industrial disc-stack centrifuges used in the bioprocess technology field. The particle settling velocity \( v_g \) typically ranges from \( 10^{-5} \) to \( 10^{-4} \text{ m s}^{-1} \).

3 Experimental

3.1 Experimental Techniques for Rheological Characterization of Disc-Stack Centrifuge Biomass Solids

Three properties are considered to characterize the rheology of the solids phase in disc-stack centrifuges. Laboratory test methods are devised for each property investigated. These methods are straightforward and quickly to apply and require only a small amount of samples of solids for testing, in total only a couple of grams. Moreover, at the same time reproducible results are achieved. Advanced laboratory instruments are used but the tests are easy to execute by the lab technician or researcher. The lab tests mimic the conditions in industrial full-scale disc-stack centrifuges and focus on both the liquid-like and solid-like behavior of the solids phase. The results from these four laboratory tests can be taken as a basis for predictions and optimization of the process performance of the centrifuge.

The three properties are the solids particle settling velocity, the angle of repose, and the apparent viscosity. Below the experimental test methods and evaluation procedures for experimental determination of these properties are described.

3.1.1 Solids Particle Settling Velocity \( v_g \)

Measurement of this parameter is performed in a Lumisizer lab centrifuge. The technique is illustrated in Fig. 3.

Figure 3. Measurement of particle settling velocity with a Lumisizer centrifuge with optical measurement technique.

The dispersion analyzer, Lumisizer, is a microprocessor-controlled analytical photo-centrifuge which allows space- and time-resolved extinction profiles in multiple samples at \( G \)-values up to 2300 \( g \). As long as the bulk liquid allows light transmission, sedimentation or creaming velocity distributions can be studied without knowing any parameters of the Stokes’ law, i.e., size distribution, density difference, and viscosity according to Eq. (4). Thus, at low transmission rates, the linearity limit of the Lambert-Beer law must be considered, i.e., the risk of erroneous estimation of settling velocity distribution.

In Fig. 4, a typical measurement in the Lumisizer is illustrated. The samples are evaluated from the top surface, meniscus, down to the bottom of the cuvette, illustrated by dotted lines. The \( x \)-axis shows the radius of rotation of the cuvette, the \( y \)-axis indicates the transmission of 870-nm light.

At the first measurement, the first red line at the lower left, the transmission of light is high only at the very top of the studied sample while at larger radii almost no light passes through. At later light transmission readings, when exposed longer time in the \( g \)-force field, the transmission value increases also at larger radii. When finally all particles have settled to the bottom, the transmission is equal throughout the whole radial field (green line).

The settling velocity measurements were performed in a Dispersion Analyzer Lumisizer 651 at 870-nm light utilizing 2-mm polyamide cuvettes. After filling of the cuvettes with feed dispersion, they were as quickly as possible mounted in the Lumisizer and spun to minimize presettling and solids interference at the polymeric cuvette surface. The rotational speed was varied between 400 and 4000 rpm depending on the settling velocities of the studied solids.

3.1.2 Angle of Repose of Solids \( \alpha \)

The angle of repose is a concept usually associated with granular flows of solid particles. In the disc-stack centrifuge design it is an important parameter, e.g., to ensure that solids, sedimenting onto the conical discs in the disc-stack will slide off and not
get stuck and block the flow, causing poor performance and need of cleaning the disc-stack. Here, the angle of repose concept is applied to biomass suspension solids, i.e., a solid-liquid system, and measured with a so-called pentometer test. The test suspension containing the solids is centrifuged in a test-tube with a conical bottom insert (Fig. 5). The test suspension is a sample from the feed stream to the disc-stack centrifuge. A metal insert with a conical surface with varying angle, $10^\circ$–$50^\circ$, is placed in the lab-bench centrifuge. The suspension is then exposed to high $g$-force for a certain period of time at process temperature.

During centrifugation, the sediment settling at the conical bottom surface will either stay on the surface or slide off depending on the angle of the insert at the location of the settled particle and the particle properties, down into a collecting chamber in the bottom of the test tube, Fig. 5. After centrifugation, the insert is removed from the holder and placed onto a nomogram. A line is drawn from the center of the insert via the outermost edge of the collected solids out to the nomogram scale. An average value from both sides of the insert gives the measured angle of repose of the solids.

The pentometer tests were performed in a laboratory swing-out centrifuge with a maximum rotational radius of 150 mm. Two cups with pentometer inserts were filled with sample liquid to the same total weight. The cups were mounted in the centrifuge and operated at 3000 rpm, 10 min, and ambient temperature, resulting in a $g$-force of 950 at the lowest insert surface and 1400 at the bottom of the cups. After centrifugation, the inserts were removed from the cups and placed on a nomogram for reading of the angle of repose from the two demarcation lines. The solids sliding off the insert, ending up at the bottom of the cups were later used in the squeeze test.

### 3.1.3 Squeeze Flow Test Measuring the Solids Apparent Viscosity $\eta$

In the squeeze flow test a sample of solids of known volume is squeezed between two parallel plates of a rheometer (Fig. 6). The upper plate is lowered at a constant speed to a defined end position. When the upper plate comes into contact with the sample to be evaluated, it forms a cylinder with increasing diameter.

$$ \sigma = \sqrt{\frac{\pi h^2}{V}} \quad (7) $$

$$ \frac{dy}{dt} = \frac{3\sqrt{\frac{V}{\pi}}}{2h^2} \quad (8) $$

$$ \eta = \frac{\sigma}{\frac{dy}{dt}} \quad (9) $$

where $\sigma$ is the shear stress, $dy/dt$ is the shear rate, and $\eta$ is the apparent viscosity.
A Malvern Kinexus lab+ rheometer instrument with 60-mm parallel plates was employed for the tests. The sample of solids used in the squeeze flow test is obtained from solids material gathered in the test tube solids collecting chamber after a completed pentometer test. After the 10-min exposure at 3000 rpm and removal of the pentometer insert, the separated liquid is decanted off, leaving a compacted solids phase at the bottom. Approximately 1 g of this close to 100 vol % solids paste is balanced onto the center of the lower rheometer plate. By determining the density of the solids paste using a pycnometer and a scale or an oscillating tube density meter (Anton Paar DMA35), depending on the solids flowability, the volume of the balanced sample is determined. After relocating the bottom plate onto the rheometer, the upper plate is lowered at 0.5–2 mm s⁻¹ while monitoring the force needed to maintain a constant velocity.

3.2 Materials

Measurement of settling speed and angle of repose of bacteria γ-amino butyric acid (GABA) together with coagulants and polyelectrolytes for increasing of agglomerate size is already described in Merkel et al. [6]. In this paper, some other biological solids from food and life science sectors have been compared to GABA and GABA flocculated with the polyelectrolyte Zetag 7587. The biological solids included as comparison are commercial tapioca starch (dispersed in tap water), commercial dry bakers’ yeast (dispersed in tap water), commercial quark (dispersed in tap water), and a mammalian cell. The GABA broth used originates from October 2016. The solids content is measured to 6 vol % via centrifugation at 1400 g for 1 h in fine-graded glass tubes, corresponding to approximately 1.5 wt %.

The linear polyelectrolyte of cationic polyacrylamide type with high charge density and medium molecular weight, Zetag 7587, is diluted in tap water to a concentration of 0.5 wt % and matured over night at slow stirring. Prior to the pentometer test, an amount corresponding to 45 g active polyelectrolyte per kg solids is added to a 250-mL beaker with approximately 100 g of GABA broth followed by mixing with a magnetic stirrer at 500 rpm for 1 min (beaker diameter 60 mm, magnet length 40 mm).

4 Results and Discussion

In this section, the results from the rheological measurements of the solids phase are presented in terms of three characteristic properties: the solids particle settling velocity \( v_g \) at 1 g, the angle of repose \( \alpha \), and the apparent viscosity of the solids phase \( \eta \).

4.1 Solids Particle Settling velocity \( v_g \)

The measured settling velocity in the Lumisizer is presented at the tested rotational speed, i.e., the g-force. In order to be able to utilize Eq. (2) and Eq. (6), the settling velocities are divided by the calculated average rotational g-force. A recalculation of the settling velocity distribution for GABA is indicated in Fig. 7. The analysis is performed at 4000 rpm resulting in an average g-force of 2162 g.

All settling velocity distributions presented in Fig. 8 have been recalculated to 1 g through the average g-force applied in each specific analysis.

The settling velocities at 1 g of included biological solids differ at least by three orders of magnitude when comparing the most difficult solid to separate, GABA, to the easiest particle to
separate, tapioca starch. The studied GABA broth contains a narrow velocity distribution between 0.03 and 0.07 μm s⁻¹. Outside of this there is thus a tail of slow settling particles, debris of ruptured cells, settling at low speeds of down to 2 nm s⁻¹.

The $V_g$ of interest for a process is the one fulfilling good-enough results in terms of customer demands. If for example a crystal-clear liquid concentrate is demanded in the centrifuge process, i.e., with no remaining particles, the lowest measured settling velocity must be applied. In the GABA case this would correspond to approximately 2 nm s⁻¹ in settling velocity. If, in the GABA case, a remaining fraction of debris is acceptable, the settling velocity can be increased at least ten times to 0.02 μm s⁻¹. This is still very much lower compared to the settling velocities found in the tapioca starch case. The slowest settling particles in the tapioca case still settle by 150 times faster, at 3 μm s⁻¹.

As an example, in an industrial process, with a medium-size high-speed centrifuge with an equivalent settling area $\Sigma$ of 100 000 m², utilizing Eq. (2), the smallest set $V_g$ for GABA would generate a $Q_t$ of maximum 0.7 m³ h⁻¹. If omitting the assumed debris, then $Q_t$ could instead reach up to 7 m³ h⁻¹.

If applying the measured tapioca starch settling velocity of 3 μm s⁻¹ in the same size of centrifuge, the resulting estimate of $Q_t$ would be >1000 m³ h⁻¹. In this case it is easy to realize that the separation is not the limiting factor, whereas hydraulic handling of the liquid, or solids, will prove more difficult.

The studied mammalian cell and bakers’ yeast settling velocity distributions are fairly equal, positioned between the GABA and the tapioca distributions, with a settling velocity of 0.5 and 1 μm s⁻¹, respectively.

It should be noted that the velocity distribution measurement performed in the Luminizer is with low shear forces compared to the inlet conditions in a disc-stack centrifuge. If the particles are shear-sensitive and if high shear forces act in the centrifuge inlet, solids may break, causing smaller particles, lower settling speeds, and reduced centrifuge capacity. The effect of shear forces, mimicking the inlet of a high-speed centrifuge, may thus be investigated in a spinning disc device, further described by Merkel et al. [6]

Setting $V_g$ to 0.002, 0.5, 1, and 3 μm s⁻¹ for total removal of solids for GABA, mammalian cell, bakers’ yeast, and tapioca starch, respectively, would give a relative settling ratio according to Tab. 1, indicating the large differences between the solids settling properties.

### Table 1. Relative ratio in settling velocity when comparing the smallest measured velocity in GABA, mammalian cell, bakers’ yeast, and tapioca starch.

| Material           | $V_{g\,\text{min}}$ [m s⁻¹] | $V_{g\,\text{max}}$ [m s⁻¹] | $A_e$ [m²] |
|--------------------|---------------------|---------------------|-------------|
| GABA               | 2.0 × 10⁻⁹          | 8.0 × 10⁻⁶          | 3.13 × 10⁻² |
| Bakers’ yeast      | 1.0 × 10⁻⁶          | 3.0 × 10⁻⁵          | 4.17 × 10⁻² |
| Mammalian cell     | 5.0 × 10⁻⁷          | 4.0 × 10⁻⁶          | 1.56 × 10⁻¹ |
| Tapioca starch     | 3.0 × 10⁻⁶          | 9.0 × 10⁻⁵          | 4.17 × 10⁻² |

### 4.2 Angle of Repose of Solids $\alpha$

The angle of repose measurement from the pentometer test reveals clear differences between the studied solids. GABA gave a moderate angle of repose around 32°. When adding a poly-electrolyte to the broth, the angle of repose increased considerably up to 45°. Quark shows the same steep angle of repose as the flocculated bacteria GABA, namely, 45°, while tapioca starch only exhibits an angle of 21°. No solids can be found on the pentometer insert after studying the bakers’ yeast and mammalian cells, indicating an angle of repose less than 10° (Fig. 9).

Process-wise this would indicate that care must be taken when choosing the angle of the conical lamellas in the disc-stack especially when processing flocculated GABA or quark. For the mammalian cell and for bakers’ yeast there are no considerations needed in terms of internal angles in the rotating bowl.

### 4.3 Squeeze Flow Test Measuring the Solids Apparent Viscosity $\eta$

A typical result from a squeeze flow test is demonstrated in Fig. 10. The downward normal plate velocity, $-d h/dt$, as well as the normal force evolution $F(t)$ are indicated. Also, the resulting viscosity as function of shear rate of the complete measurement cycle is shown. Since the flow rates of solids not are constant at the start of the measurement, when no solids cylinder yet has been formed, and at the end when the upper plate stop at the end position and flow starts to cease, these data are omitted when presenting the apparent viscosity. The red rings in Fig. 10 indicate the typically removed start data while the black ring denotes the typically removed end data.
These solids samples are all close to 100 vol % after the compaction at 1400 g (the g-force cannot squeeze out more liquid). The solids weight ratio may thus differ significantly mainly depending on the intracellular water amount but also slightly from the shape of the solids (small amount of free space between particles).

The rheology of the solids tested is shear-thinning, as shown by the decreasing slope, in all samples but one, the tapioca starch. Apart from tapioca, the solids viscosities vary approximately three orders of magnitude in a shear range from 1 to 1000 s⁻¹; the higher the shear rate, the lower the apparent viscosity (Fig. 11).

The tapioca starch is shear-thickening and hence increases in viscosity when the shear rate rises. Despite the promising angle of repose, 21°, and the high settling velocity, > 3 μm s⁻¹, the viscosity behavior directly indicates issues with a continuous solids outlet; the more shear added to force the solids, the more they resist. A high-speed centrifuge with continuous solids transportation in opposite direction to the g-force cannot be applied on tapioca.

A shear rate of 100 s⁻¹ is representative for continuous solids transportation rates in high-speed centrifuges (Tab. 3). At this shear rate the GABA solids have a viscosity close to 1 Pa s. Upon adding 45 g active Zetag 7587 per kg biomass, the viscosity increases to above 5 Pa s. From a continuous solids outlet perspective, it will thus be a larger challenge forcing the flocculated material out of the high-speed centrifuge compared to the untreated GABA material, and a too high feed pressure may result.

Concentrated solids of quark and flocculated GABA have similar apparent viscosities at a shear rate of 100 s⁻¹, namely, 4–5.5 Pa s. Since they have the same angle of repose, 45°, these two solids would demand similar settings of the high-speed centrifuge, especially if the settling velocities also are the same.

The angle of repose of bakers’ yeast was found below 10° but the apparent viscosity is higher than of GABA, i.e., 1.5 Pa s compared to approximately 0.85 Pa s. The mammalian cells are found to have the lowest viscosity with 0.23 Pa s at 100 s⁻¹. In a high-speed centrifuge process with continuous solids transportation in opposite direction to the g-force, mammalian cells would be the easiest of the examined solids to be forced out opposite the g-force in a high-speed centrifuge.

5 Conclusions

- The angle of repose test can give direct information how to configure internal angles in the high-speed centrifuge, especially for the conical lamellas.
- The viscosity versus shear behavior provides information whether continuous solids transportation opposite the g-force can be applied or not.

Figure 9. Pentometer inserts after angle of repose test. From left, GABA (a), GABA + Zetag 7587 (b), quark (c), tapioca starch (d), bakers’ yeast and mammalian cell (e).

Figure 10. Typical squeeze flow results. The upper plate velocity, −dh/dt, and the normal force evolution F(t) are indicated in (a). Resulting apparent viscosity as function of shear rate of the complete measurement cycle (b).

Figure 11. Apparent viscosity versus shear rate from squeeze flow test on mammalian cell, tapioca starch, quark, baker’s yeast, GABA, and GABA with added flocculant Zetag 7587.
The measured settling velocities directly indicate the size of the needed centrifuge for a given task or possible capacity through a given centrifuge.

Utilizing only a small fraction of solids sample, the three methods shown can together build an understanding on how to configure a high-speed centrifuge as well as predicting the possible capacity in an industrial full-scale process.

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Symbols used

| Symbol | Definition |
|--------|------------|
| \( A \) | cross-sectional area |
| \( c \) | volume fraction concentration of solids |
| \( d \) | solids particle diameter |
| \( D \) | annular gap between cylinder piston and test tube |
| \( F \) | acceleration in gravitational field, \( 1g = 9.82 \text{ m s}^{-2} \) |
| \( g \) | centrifugal acceleration factor relative to \( 1g \) at radius \( r \) |
| \( FL \) | correction factor in \( \Sigma \) for disc-stack centrifuges |
| \( h \) | height between plates in squeeze flow test |
| \( m \) | piston mass |
| \( n \) | number of discs in disc-stack centrifuges |
| \( Q \) | volumetric flow rate |
| \( r \) | radial position in disc-stack centrifuge or test tube |
| \( r_1 \) | inner radius of discs in disc-stack centrifuges |
| \( r_2 \) | outer radius of discs in disc-stack centrifuges |
| \( t \) | time |
| \( T \) | time in centrifugal force field |
| \( U \) | bulk flow velocity |
| \( V \) | solids sample volume in squeeze flow test |
| \( v \) | normal downward plate velocity in squeeze flow test |
| \( v_g \) | particle settling velocity in gravitational field, \( 1g \) |
| \( x \) | piston penetration distance into solids sediment |

Greek letters

| Symbol | Definition |
|--------|------------|
| \( \alpha \) | angle of repose |
| \( \mu \) | dynamic viscosity of Newtonian suspension carrier fluid |
| \( \eta \) | apparent viscosity of suspension solids phase |
| \( \Delta \rho \) | density difference between liquid and solid phases |
| \( \omega \) | angular rotation frequency of disc-stack centrifuge or test tube |
| \( \Sigma \) | equivalent settling area of disc-stack centrifuge |
| \( \sigma \) | shear stress |
| \( dy/dt \) | shear rate |
| \( \theta \) | half disc angle |

Sub- and superscripts

| Symbol | Definition |
|--------|------------|
| \( 0 \) | initial |
| \( e \) | effluent stream, effective residence time |
| \( f \) | feed stream |
| \( s \) | solids stream |

Abbreviation

GABA \( \gamma \)-amino butyric acid

Table 3. Relative ratio in apparent viscosity at a shear rate of 100 s\(^{-1}\) for mammalian cell, GABA, bakers’ yeast quark, and GABA with Zetag 7587.

|          | Mammalian cell | GABA | Baker’s yeast | Quark | Gaba + Zetag7587 |
|----------|----------------|------|---------------|-------|-----------------|
| Mammalian cell | 1    | 3.5  | 6.2           | 16.7  | 22.9            |
| GABA     | 0.3  | 1    | 1.8           | 4.7   | 6.5             |
| Baker’s yeast | 0.16 | 0.6  | 1             | 2.7   | 3.7             |
| Quark    | 0.06 | 0.2  | 0.4           | 1     | 1.4             |
| Gaba + Zetag7587 | 0.04 | 0.1  | 0.3           | 0.7   | 1               |
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