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Institut für Strömungslehre und Wärmeübertragung
Department of Particulate Flow Modelling

Materials to Simulations to Applications

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Motivation and State Of The Art

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Chapter 1

Insufficiency of the State of the Art

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Chapter 2

Discrete Element Model

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Chapter 3

Computational Fluid Dynamics

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Artificial Neural Network

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Part III

Identification

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Chapter 5

DEM Parameters

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5.1 Literature Values

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5.2 Particle Distribution

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5.3 Bulk Density

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5.4 Angle of Repose (p-p) - Small Scale

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5.5 Angle of Repose (p-p) - Large Scale

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5.6 Angle of Repose Simulation

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5.7 Maximum Static Angle (p-w)

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5.8 Maximum Static Angle Simulation

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5.9 Schulze Ring Shear Cell tester (p-p)

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5.10 Jenike Shear Cell tester

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5.10.1 p-p

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5.10.1.1 Instructions

5.10.1.1.1 Scope

5.10.1.1.1.1 This method covers the apparatus and procedures for measuring the cohesive strength of bulk solids during both continuous flow and after storage at rest. In addition, measurements of internal friction, bulk density, and wall friction on various wall surfaces are included.

5.10.1.1.1.2 This standard is not applicable to testing bulk solids that do not reach the steady state requirement within the travel limit of the shear cell. It is impossible to classify ahead of time which bulk solids cannot be tested, but one example may be those consisting of highly elastic particles.

5.10.1.1.1.3 The values stated in SI units are to be regarded as standard.

5.10.1.1.1.4 The most common use of this information is in the design of storage bins and hoppers to prevent flow stoppages due to arching and ratholing, including the slope and smoothness of hopper walls to provide mass flow. Parameters for structural design of such equipment also may be derived from this data.

5.10.1.1.2 Terminology

5.10.1.1.2.1 Definitions of terms used in this test method are in accordance with Terminology D653.

5.10.1.1.2.2 adhesion test , a static wall friction test with time consolidation.

5.10.1.1.2.3 angle of internal friction , ϕ_e, the angle between the axis of normal stress (abscissa) and the tangent to the yield locus.

5.10.1.1.2.4 angle of wall friction , ϕ_w, the arctan of the ratio of the wall shear stress to the wall normal stress.

5.10.1.1.2.5 bin , a container or vessel for holding a bulk solid, frequently consisting of a vertical cylinder with a converging hopper. Sometimes referred to as silo, bunker, or elevator.

5.10.1.1.2.6 bulk density , ρ_b, the mass of a quantity of a bulk solid divided by its total volume.

5.10.1.1.2.7 bulk solid , an assembly of solid particles handled in sufficient quantities that its characteristics can be described by the properties of the mass of particles rather than the characteristics of each individual particle. May also be referred to as granular material, particulate solid, or powder. Examples are sugar, flour, ore, and coal. 3.1.8 bunker, synonym for bin, but sometimes understood as being a bin without any or only a small vertical part at the top of the hopper. 3.1.9 cohesive strength, synonym for unconfined yield strength. 3.1.10 consolidation, the process of increasing the strength of a bulk solid. 3.1.11 critical state, a state of stress in which the bulk density of a bulk solid and the shear stress in the shear zone remain constant. 3.1.12 effective angle of friction, δ, the inclination of the effective yield locus (EYL). 3.1.13 effective yield locus (EYL), straight line passing through the origin of the σ, τ-plane and tangential to the steady state Mohr circle, corresponding to steady state flow conditions of a bulk solid of given bulk density. 3.1.14 elevator, synonym for bin, commonly used in the grain industry. 3.1.15 failure (of a bulk solid), plastic deformation of an overconsolidated bulk solid subject to shear, causing dilation and a decrease in strength. 3.1.16 flow, steady state, continuous plastic deformation of a bulk solid at critical state. 3.1.17 flow function, FF, the plot of unconfined yield strength versus major consolidation stress for one specific bulk solid. 3.1.18 granular material, synonym for bulk solid. 3.1.19 hopper, the converging portion of a bin. 3.1.20 major consolidation stress, σ_1, the major principal stress given by the Mohr stress circle of steady state flow. This Mohr stress circle is tangential to the effective yield locus. 3.1.21 Mohr stress circle, the graphical representation of a state of stress in coordinates of normal and shear stress, that is, in the σ, τ-plane. 3.1.22 normal stress, σ, the stress acting normally to the considered plane. 3.1.23 overconsolidated specimen, a condition in which the shear force passes through a maximum and then decreases during preshear. 3.1.24 particulate solid, synonym for bulk solid. 3.1.25 powder, synonym for bulk solid, particularly when the particles of the bulk solid are fine. 3.1.26 silo, synonym for bin. 3.1.27 shear test, an experiment to determine the flow properties of a bulk solid by applying different states of stress and strain to it. 3.1.28 shear tester, an apparatus for performing shear tests. 3.1.31 unconfined yield strength, f_c, the major principal stress of the Mohr stress circle being tangential to the yield locus with the minor principal stress being zero.A synonym for compressive strength. 3.1.32 underconsolidated specimen, a condition in which the shear force increases continually during preshear. 3.1.33 wall normal stress, σ_w, the normal stress present at a confining wall. 3.1.34 wall shear stress, τ_w, the shear stress present at a confining wall. 3.1.35 wall yield locus, a plot of the wall shear stress versus wall normal stress. The angle of wall friction is obtained from the wall yield locus as the arctan of the ratio of the wall shear stress to wall normal stress. 3.1.36

yield locus, plot of shear stress versus normal stress at failure. The yield locus (YL) is sometimes called the instantaneous yield locus to differentiate it from the time yield locus.

4. Summary of Test Method 4.1 A representative sample of bulk solid is placed in a shear cell of specific dimensions. This specimen is preconsolidated by twisting the shear cell cover while applying a compressive load normal to the cover. 4.2 When running an instantaneous , a normal load is applied to the cover, and the specimen is presheared until a steady state shear value has been reached.
4.3 An instantaneous test is run by shearing the specimen under a reduced normal load until the shear force goes through a maximum value and then begins to decrease.
4.5 A wall friction test is run by sliding the specimen over a coupon of wall material and measuring the frictional resistance as a function of normal, compressive load.

5. Significance and Use
5.1 Reliable, controlled flow of bulk solids from bins and hoppers is essential in almost every industrial facility. Unfortunately, flow stoppages due to arching and ratholing are common. Additional problems include uncontrolled flow (flooding) of powders, segregation of particle mixtures, useable capacity which is significantly less than design capacity, caking and spoilage of bulk solids in stagnant zones, and structural failures.
5.2 By measuring the flow properties of bulk solids, and designing bins and hoppers based on these flow properties, most flow problems can be prevented or eliminated.
5.3 For bulk solids with a significant percentage of particles (typically, one third or more) finer than about 6 mm (1/4 in.), the cohesive strength is governed by the fines (6mm fraction). For such bulk solids, cohesive strength and wall friction tests may be performed on the fine fraction only.
NOTE 1: The quality of the result produced by this test method is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used.

6. Apparatus 6.1 The Jenike shear cell is shown in **Fig. 1**. It consists of a base (1), shear ring (2), and shear lid (3), the latter having a bracket (4) and pin (5). Before shear, the ring is placed in an offset position as shown in **Fig. 1**, and a vertical force F_v is applied to the lid, and hence, to the particulate solid within the cell by means of a weight hanger (6) and weights (7). A horizontal force is applied to the bracket by a mechanically driven measuring stem (8).
6.2 It is especially important that the shear force measuring stem acts on the bracket in the shear plane (plane between base and shear ring) and not above or below this plane.
6.3 The dimensions of the Jenike shear cells supplied by Jenike and Johanson, Inc. are given in the first two columns of the table in **Fig. 4**. These dimensions have been derived from English units. The standard size Jenike shear cell is made from aluminum or stainless steel, and a smaller 63mm diameter cell made from stainless steel is also available. Since the actual dimensions are not believed to be critical, the same results could be obtained with a shear cell of the dimensions listed in the third column of the table in **Fig. 4** or with other shear cells

of different sizes provided that proportions of these dimensions are maintained approximately. In addition, **the shear cell diameter must be at least 20 times the maximum particle size of the bulk solid being tested**. Besides the shear cell, the complete shear tester includes a force transducer which measures the shear force F_s, an amplifier and a recorder, a motor driving the force measuring stem, a twisting wrench, a weight hanger, an accessory for mounting wall material sample plates, and a calibrating device. A spatula having a blade at least 50 is needed. The force transducer should be capable of measuring a force up to 300 N with a precision of 0.1 a recorder. The motor driving the force measuring stem advances the stem at a constant speed in the range from 1 to 3 mm/min.

7. Specimen Preparation

7.1 Filling the Cell **Fig. 8**:

7.1.1 Place the shear ring on the base in the offset position shown in **Fig. 1** and gently press the ring with the fingers against the locating screws (10) as shown in Fig. 3 and Fig. 9. Set these screws to give an overlap of approximately 3 mm for standard cell sizes and to ensure that the axis of the cell is aligned with the force measuring stem. Then place the mould ring (11) on the shear ring.

7.1.2 Fill the assembled cell uniformly in small horizontal layers by a spoon or spatula without applying force to the surface of the material until the material is somewhat over the top of the mould ring. The filling should be conducted in such a way as to ensure that there are no voids within the cell, particularly at ??????? **Fig. 8** where the ring and the base overlap. Remove excess material in small quantities by scraping off with a blade (1). The blade should be scraped across the ring in a zig-zag motion. Take care not to disturb the position of the ring on the base. For scraping, a rigid sharp straight blade should be used, and, during scraping, the blade should be tilted as shown in **Fig. 8**.

7.2 Preconsolidation:

7.2.1 Place the twisting or consolidation lid (12) shown in **Fig. 9** on the leveled surface of the material in the mould, then place the hanger (6) on the twisting lid with weights (7) of mass m_{Wtw} being hung from the hanger. See **Fig. 1**. Lower the lid, hanger, and weights as slowly as possible to minimize aerated material being ejected from the cell.

7.2.2 Visually observe the vertical movement of the lid as the material of the cell is compressed.Wait until this movement appears to stop.

7.2.3 Remove the weights, hanger, and twisting lid. Fill and level the space above the compressed material as during filling.

NOTE 3: As will be mentioned later, this refilling procedure may not be necessary at all or may need to be performed several times, depending on the compressibility of the powder being tested. This operation determines what height of compacted material will have to be scraped off the ring after twisting.

7.3 Twisting:

7.3.1 Place the twisting lid (12) with a smooth bottom surface on the leveled surface of material in the mould after filling or refilling. Place the hanger with weights of m_{Wtw} on the twisting lid. The weights on the hanger should correspond to a pressure of σ_{tw}, approximately equal to σ_p.

7.3.2 Empty the cell and repeat the filling operation if the surface of material in

the cell does not appear to the naked eye to be level.
7.3.3 Having filled the cell, the twisting lid is usually twisted through 20 cycles by means of the twisting wrench (spanner) (13) or twisting device. Each twisting cycle consists of a 90 *degrees* rotation of the lid which is then reversed. Care must be taken not to apply vertical forces to the lid during twisting. While twisting, press the ring against the locating screws with the fingers to prevent it from sliding from its original offset position.

5.10.2 p-w

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5.11 Shear Cell Simulation

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5.12 Coefficient of Restitution

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5.12.1 p-p

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5.12.2 p-w

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5.13 Coefficient of Restitution Simulation - Estimation Matlab

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Chapter 6

CFD Parameters

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6.1 Pressure Drop Test (p-p and p-w)

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6.2 Pressure Drop Test Simulation

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Part IV

Coupled Behavior of Numerical Parameters

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Chapter 7

Artificial Neural Network Training

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Chapter 8

Influence of variations of input parameters and poly-dispersity

the influence of variations (distributions) of input parameters and poly-dispersity

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Chapter 9

Behavior extrapolation and prediction

the possbility to extrapolate (e.g. given 3 different fraction distributions, with known behaviors, extrapolate the behavior of a fourth fraction distribution).

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9.1 Confrontation with AOR Large Scale

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Chapter 10

Validation

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10.1 Mass Hopper Flow (p-p and p-w) - Validation 1

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10.2 Mass Hopper Flow Simulation - Validation 1

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Part V

Applications

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Chapter 11

Sinter Plant

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Chapter 12

Blast Furnace

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Bibliography

[1] Jun Ai et al. "Assessment of rolling resistance models in discrete element simulations". In: *Powder Technology* 206.3 (2011), pp. 269–282.

[2] Andreas Aigner et al. "Comparison of simulation and experimental results of a simplified jenike shear tester". In: Colorado School of Mines, 2013.

[3] Andreas Aigner et al. "Determining the coefficient of friction by shear tester simulation". In: 2013, pp. 335–342.

[4] A. Alenzi et al. "DEM validation using an annular shear cell". In: *Powder Technology* 248.0 (Nov. 2013), pp. 131–142.

[5] S. J. Antony, C. H. Zhou, and X. Wang. "An integrated mechanistic-neural network modelling for granular systems". In: *Applied Mathematical Modelling* 30.1 (Jan. 2006), pp. 116–128.

[6] D. Aole, M. K. Jain, and M. Bruhis. "New characterization methods for powder die fill process for producing powder metallurgical components". In: *Powder Technology* 232.0 (Dec. 2012), pp. 7–17.

[7] International ASTM. *ASTM D6128 - 06 - Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell.* 2013.

[8] International ASTM. *ASTM D6773 - 02 - Standard Shear Test Method for Bulk Solids Using the Schulze Ring Shear Tester.* 2013.

[9] Reza Barati, Seyed Ali Akbar Salehi Neyshabouri, and Goodarz Ahmadi. "Development of empirical models with high accuracy for estimation of drag coefficient of flow around a smooth sphere: An evolutionary approach". In: *Powder Technology* 257.0 (May 2014), pp. 11–19.

[10] Dana Barrasso, Ashutosh Tamrakar, and Rohit Ramachandran. "A reduced order PBM-ANN model of a multi-scale PBM-DEM description of a wet granulation process". In: *Chemical Engineering Science* 0 ().

[11] Gabriel K. P. Barrios et al. "Contact parameter estimation for DEM simulation of iron ore pellet handling". In: *Powder Technology* 248.0 (Nov. 2013), pp. 84–93.

[12] Niranjana Behera et al. "Modeling and analysis of dilute phase pneumatic conveying of fine particles". In: *Powder Technology* 249.0 (Nov. 2013), pp. 196–204.

[13] R. J. Berry and M. S. A. Bradley. "Investigation of the effect of test procedure factors on the failure loci and derived failure functions obtained from annular shear cells". In: *Powder Technology* 174.1-2 (2007), pp. 60–63.

[14] Tathagata Bhattacharya and J. J. McCarthy. "Chute flow as a means of segregation characterization". In: *Powder Technology* 256.0 (Apr. 2014), pp. 126–139.

[15] Giuseppe Boccignone. *Computazione per interazione naturale: Regressione lineare Bayesiana.*

[16] L. J. Briggs. "Methods for measuring the coefficient of restitution and the spin of a ball". In: *Journal of Research of the National Bureau of Standards* 34 (1945).

[17] Chris Brown and Randal Nelson. *Fitting Experimental Data.* 2011.

[18] Petra Bubakova, Martin Pivokonsky, and Petr Filip. "Effect of shear rate on aggregate size and structure in the process of aggregation and at steady state". In: *Powder Technology* 235.0 (Feb. 2013), pp. 540–549.

[19] Jeffrey W. Bullard and Edward J. Garboczi. "Defining shape measures for 3D star-shaped particles: Sphericity, roundness, and dimensions". In: *Powder Technology* 249.0 (Nov. 2013), pp. 241–252.

[20] Aykut Canakci, Sukru Ozsahin, and Temel Varol. "Modeling the influence of a process control agent on the properties of metal matrix composite powders using artificial neural networks". In: *Powder Technology* 228.0 (Sept. 2012), pp. 26–35.

[21] John W. Carson and Harald Wilms. "Development of an international standard for shear testing". In: *Powder Technology* 167.1 (2006), pp. 1–9.

[22] A. Lumin Chen, B. Zhen Chen, and C. Ansheng Feng. "Image analysis algorithm and verification for on-line molecular sieve size and shape inspection". In: *Advanced Powder Technology* 0 ().

[23] Sebastian Chialvo, Jin Sun, and Sankaran Sundaresan. "Bridging the rheology of granular flows in three regimes". In: *Phys.Rev.E* 85.2 (2012), p. 021305. URL: http://link.aps.org/doi/10.1103/PhysRevE.85.021305.

[24] Arthur Christopoulos and Michael J. Lew. "Beyond eyeballing: fitting models to experimental data". In: *Critical reviews in biochemistry and molecular biology* 35.5 (2000), pp. 359–391.

[25] Paul W. Cleary, Rob Morrisson, and Steve Morrell. "Comparison of DEM and experiment for a scale model SAG mill". In: *International Journal of Mineral Processing* 68.1-4 (Jan. 2003), pp. 129–165.

[26] Paul W. Cleary and Mark L. Sawley. "DEM modelling of industrial granular flows: 3D case studies and the effect of particle shape on hopper discharge". In: *Applied Mathematical Modelling* 26.2 (Feb. 2002), pp. 89–111.

[27] C. J. Coetzee and R. G. Nel. "Calibration of discrete element properties and the modelling of packed rock beds". In: *Powder Technology* 264.0 (Sept. 2014), pp. 332–342.

[28] Kevin D. Costa, Steven Kleinstein, and Uri Hershberg. *Model Fitting and Error Estimation.* 2010.

[29] Shyamal C. Das et al. "Importance of particle size and shape on the tensile strength distribution and de-agglomeration of cohesive powders". In: *Powder Technology* 249.0 (Nov. 2013), pp. 297–303.

[30] Niklas Engblom et al. "Segregation of powder mixtures at filling and complete discharge of silos". In: *Powder Technology* 215-216.0 (Jan. 2012), pp. 104–116.

[31] Zhi-Gang Feng and Samuel Gem Musong. "Direct numerical simulation of heat and mass transfer of spheres in a fluidized bed". In: *Powder Technology* 262.0 (Aug. 2014), pp. 62–70.

[32] P. Frankowski et al. "Material characterisation for Discrete Element Modelling calibration". In: *III International Conference on Particle-based Methods - Fundamentals and Applications PARTICLES 2013* (2013).

[33] V. Ganesan, K. A. Rosentrater, and K. Muthukumarappan. "Flowability and handling characteristics of bulk solids and powders, a review with implications for DDGS". In: *Biosystems Engineering* 101.4 (Dec. 2008), pp. 425–435.

[34] D. Geldart, E. C. Abdullah, and A. Verlinden. "Characterisation of dry powders". In: *Powder Technology* 190.1-2 (2009), pp. 70–74.

[35] LaTosha M. Gibson et al. "Image analysis measurements of particle coefficient of restitution for coal gasification applications". In: *Powder Technology* 247.0 (Oct. 2013), pp. 30–43.

[36] Christoph Goniva et al. "Influence of rolling friction on single spout fluidized bed simulation". In: *Particuology* 10.5 (Oct. 2012), pp. 582–591.

[37] Yan Grasselli and Hans J. Herrmann. "On the angles of dry granular heaps". In: *Physica A: Statistical Mechanics and its Applications* 246.3-4 (1997), pp. 301–312.

[38] Yan Grasselli et al. "Effect of impact energy on the shape of granular heaps". English. In: 2.2 (2000). journal: Granular Matter, pp. 97–100. URL: http://dx.doi.org/10.1007/s100350050039.

[39] Pierre A. Gremaud, John V. Matthews, and Meghan O'Malley. "On the computation of steady Hopper flows: II: von Mises materials in various geometries". In: *Journal of Computational Physics* 200.2 (2004), pp. 639–653.

[40] Pierre A. Gremaud, John V. Matthews, and David G. Schaeffer. "On the computation of steady hopper flows III: Model comparisons". In: *Journal of Computational Physics* 219.1 (2006), pp. 443–454.

[41] A. P. Grima and P. W. Wypych. "Investigation into calibration of discrete element model parameters for scale-up and validation of particle-structure interactions under impact conditions". In: *Powder Technology* 212.1 (2011), pp. 198–209.

[42] Richard F. Grossman and R. J. Del Vecchio. "Chapter 22 : Design of Experiments". In: Handbook of Vinyl Formulating. Wiley - Interscience, 2008, p. 515.

[43] Jie Guo, Alan W. Roberts, and Jan-Dirk Prigge. "Experimental investigation of wall pressure and arching behavior under surcharge pressure in mass-flow hoppers". In: *Powder Technology* 258.0 (May 2014), pp. 272–284.

[44] V. K. Gupta and Shivani Sharma. "Analysis of ball mill grinding operation using mill power specific kinetic parameters". In: *Advanced Powder Technology* 0 ().

[45] K. Gurney. *An Introduction to Neural Networks*. Taylor and Francis, 2003. ISBN: 9780203451519. URL: http://books.google.com.pk/books?id=sn6oBHq8qQQC.

[46] G. Gustafsson et al. "Determination of bulk properties and fracture data for iron ore pellets using instrumented confined compression experiments". In: *Powder Technology* 241.0 (June 2013), pp. 19–27.

[47] Kevin J. Hanley et al. "Application of Taguchi methods to DEM calibration of bonded agglomerates". In: *Powder Technology* 210.3 (2011), pp. 230–240.

[48] Johannes Hartl and Jin Y. Ooi. "Numerical investigation of particle shape and particle friction on limiting bulk friction in direct shear tests and comparison with experiments". In: *Powder Technology* 212.1 (2011), pp. 231–239.

[49] S. S. Haykin. *Neural Networks and Learning Machines*. v. 10. 2008034079. Prentice Hall, 2009. ISBN: 9780131471399. URL: http://books.google.com.pk/books?id=K7P36lKzI_QC.

[50] Jon Hilden et al. "Note on the interpretation of powder shear test data". In: *Powder Technology* 182.3 (2008), pp. 486–492.

[51] M. Hirota et al. "Proposal of an approximation equation for the yield locus to evaluate powder properties". In: *Advanced Powder Technology* 18.3 (2007), pp. 287–302.

[52] D. Hohner, S. Wirtz, and V. Scherer. "A numerical study on the influence of particle shape on hopper discharge within the polyhedral and multi-sphere discrete element method". In: *Powder Technology* 226.0 (Aug. 2012), pp. 16–28.

[53] Richard G. Holdich. *Fundamentals of Particle Technology*. Midland Information, Technology, and Publishing, 2002.

[54] Etienne Horn. *The Calibration of Material Properties for Use in Discrete Element Models*. 2012.

[55] S. Humby, U. Tuzun, and A. B. Yu. "Prediction of hopper discharge rates of binary granular mixtures". In: *Chemical Engineering Science* 53.3 (Feb. 1998), pp. 483–494.

[56] Kazuyoshi Iwashita and Masanobu Oda. "Rolling Resistance at Contacts in Simulation of Shear band Development by DEM". In: *Journal of Engineering Mechanics* 124.3 (1998), pp. 285–292.

[57] R. J. M. Janssen, M. J. Verwijs, and B. Scarlett. "Measuring flow functions with the Flexible Wall Biaxial Tester". In: *Powder Technology* 158.1-3 (2005), pp. 34–44.

[58] M. J. Jiang, H. S Yu, and D. Harris. "A novel discrete model for granular material incorporating rolling resistance". In: *Computers and Geotechnics* 32.5 (July 2005), pp. 340–357.

[59] Kerry Johanson. "Effect of particle shape on unconfined yield strength". In: *Powder Technology* 194.3 (2009), pp. 246–251.

[60] Mohammad Khalilitehrani, Per J. Abrahamsson, and Anders Rasmuson. "The rheology of dense granular flows in a disc impeller high shear granulator". In: *Powder Technology* 249.0 (Nov. 2013), pp. 309–315.

[61] A. H. Kharaz, D. A. Gorham, and A. D. Salman. "Accurate measurement of particle impact parameters". In: *Measurement Science and Technology* 10.1 (1999), p. 31. URL: http://stacks.iop.org/0957-0233/10/i=1/a=009.

[62] A. H. Kharaz, D. A. Gorham, and A. D. Salman. "An experimental study of the elastic rebound of spheres". In: *Powder Technology* 120.3 (2001), pp. 281–291.

[63] JuHyeon Kim and SangHwan Lee. "Modeling drag force acting on the individual particles in low Reynolds number flow". In: *Powder Technology* 261.0 (July 2014), pp. 22–32.

[64] Christoph Kloss and Christoph Goniva. *LIGGGHTS Manual*. URL: http://www.cfdem.com/.

[65] Christoph Kloss et al. "Models, algorithms and validation for opensource DEM and CFDDEM". In: *Progress in Computational Fluid Dynamics, an International Journal* 12.2 (2012), pp. 140–152. URL: http://dx.doi.org/10.1504/PCFD.2012.047457.

[66] R. Kobylka and M. Molenda. "DEM simulations of loads on obstruction attached to the wall of a model grain silo and of flow disturbance around the obstruction". In: *Powder Technology* 256.0 (Apr. 2014), pp. 210–216.

[67] Matthew Krantz, Hui Zhang, and Jesse Zhu. "Characterization of powder flow: Static and dynamic testing". In: *Powder Technology* 194.3 (2009), pp. 239–245.

[68] H. Kruggel-Emden, S. Wirtz, and V. Scherer. "An analytical solution of different configurations of the linear viscoelastic normal and frictional-elastic tangential contact model". In: *Chemical Engineering Science* 62.23 (Dec. 2007), pp. 6914–6926.

[69] M. Kheiripour Langroudi et al. "An investigation of frictional and collisional powder flows using a unified constitutive equation". In: *Powder Technology* 197.1-2 (2010), pp. 91–101.

[70] M. Lashkarbolooki, B. Vaferi, and M. R. Rahimpour. "Comparison the capability of artificial neural network (ANN) and EOS for prediction of solid solubilities in supercritical carbon dioxide". In: *Fluid Phase Equilibria* 308.1-2 (2011), pp. 35–43.

[71] H. Li, G. R. McDowell, and I. S. Lowndes. "A laboratory investigation and discrete element modeling of rock flow in a chute". In: *Powder Technology* 229.0 (Oct. 2012), pp. 199–205.

[72] Stefan Luding. “Introduction to Discrete Element Methods, Basics of Contact Force Models and how to perform the MicroMacro Transition to Continuum Theory”. In: *EJECE* 12 (2008), pp. 785–826.

[73] G. Lumay et al. “Measuring the flowing properties of powders and grains”. In: *Powder Technology* 224.0 (July 2012), pp. 19–27.

[74] Tankeo M., Richard P., and Canot E. “Analytical solution of the mu-i-rheology for fully developed granular flows in simple configurations”. In: *ArXiv e-prints* (2013). 1309.2267; Provided by the SAONASA Astrophysics Data System. URL: httpadsabs.harvard.eduabs2013arXiv1309.2267T.

[75] Mohan Medhe, B. Pitchumani, and J. Tomas. “Flow characterization of fine powders using material characteristic parameters”. In: *Advanced Powder Technology* 16.2 (2005), pp. 123–135.

[76] J. Mellmann, T. Hoffmann, and C. Furll. “Flow properties of crushed grains as a function of the particle shape”. In: *Powder Technology* 249.0 (Nov. 2013), pp. 269–273.

[77] Hiroshi Mio et al. “Validation of Particle Size Segregation of Sintered Ore during Flowing through Laboratory-scale Chute by Discrete Element Method”. In: *ISIJ International* 48.12 (2008). journal: ISIJ International, pp. 1696–1703.

[78] B. K. Mishra and Raj K. Rajamani. “The discrete element method for the simulation of ball mills”. In: *Applied Mathematical Modelling* 16.11 (Nov. 1992), pp. 598–604.

[79] Paul A. Moysey, Nadella V. Rama Rao, and Malcolm H. I. Baird. “Dynamic coefficient of friction and granular drag force in dense particle flows: Experiments and DEM simulations”. In: *Powder Technology* 248.0 (Nov. 2013), pp. 54–67.

[80] Patric Muller et al. “Complex Velocity Dependence of the Coefficient of Restitution of a Bouncing Ball”. In: *Phys.Rev.Lett.* 110.25 (2013), p. 254301. URL: http://link.aps.org/doi/10.1103/PhysRevLett.110.254301.

[81] Emilia Nowak et al. “Measurements of contact angle between fine, non-porous particles with varying hydrophobicity and water and non-polar liquids of different viscosities”. In: *Powder Technology* 250.0 (Dec. 2013), pp. 21–32.

[82] W. L. Oberkampf and C. J. Roy. *Verification and Validation in Scientific Computing*. Cambridge University Press, 2010. ISBN: 9781139491761. URL: http://books.google.com.pk/books?id=7d26zLEJ1FUC.

[83] J. R. Pillai, M. S. A. Bradley, and R. J. Berry. “Comparison between the angles of wall friction measured on an on-line wall friction tester and the Jenike wall friction tester”. In: *Powder Technology* 174.1-2 (2007), pp. 64–70.

[84] Sophie L. Pirard et al. “Motion of carbon nanotubes in a rotating drum: The dynamic angle of repose and a bed behavior diagram”. In: *Chemical Engineering Journal* 146.1 (2009), pp. 143–147.

[85] S. J. Plimpton. “Fast Parallel Algorithms for Short-Range Molecular Dynamics”. In: *J Comp Phys* 117 (1995), pp. 1–19.

[86] Yury V. Polezhaev and I. V. Chircov. “DRAG COEFFICIENT”. In: *Thermopedia* (2011). URL: http://www.thermopedia.com/content/707/.

[87] Thorsten Poschel and Thomas Schwager. *Computational Granular Dynamics*. Springer, 2004.

[88] C J Reagle et al. “Measuring the coefficient of restitution of high speed microparticle impacts using a PTV and CFD hybrid technique”. In: *Measurement Science and Technology* 24.10 (2013), p. 105303. URL: http://stacks.iop.org/0957-0233/24/i=10/a=105303.

[89] Alberto Di Renzo and Francesco Paolo Di Maio. “Comparison of contactforce models for the simulation of collisions in DEMbased granular flow codes”. In: *Chemical Engineering Science* 59.3 (Feb. 2004), pp. 525–541.

[90] Rudiger Schmitt and Hermann Feise. “Influence of Tester Geometry, Speed and Procedure on the Results from a Ring Shear Tester”. In: *Particle and Particle Systems Characterization* 21.5 (2004), pp. 403–410.

[91] Dietmar Schulze. *Flow Properties of Powders and Bulk Solids*. 2011.

[92] Dietmar Schulze. *Powders and bulk solids: behavior, characterization, storage and flow*. Springer, 2008.

[93] Dietmar Schulze, H. Heinrici, and H. Zetzener. “The Ring Shear Tester as a Valuable Tool for Silo Design and Powder Characterization”. In: *Powder Handling and Processing* 13.19-26 (2001).

[94] Jorg Schwedes. “Measurement of flow properties of bulk solids”. In: *Powder Technology* 88.3 (Sept. 1996), pp. 285–290.

[95] Jorg Schwedes. “Review on testers for measuring flow properties of bulk solids”. English. In: 5.1 (2003). journal: Granular Matter, pp. 1–43. URL: http://dx.doi.org/10.1007/s10035-002-0124-4.

[96] A. Schweiger and I. Zimmermann. “A new approach for the measurement of the tensile strength of powders”. In: *Powder Technology* 101.1 (1999), pp. 7–15.

[97] Abd-Krim Seghouane, Yassir Moudden, and Gilles Fleury. “Regularizing the effect of input noise injection in feedforward neural networks training”. English. In: *Neural Computing and Applications* 13.3 (2004). J2: Neural Comput and Applic, pp. 248–254. URL: http://dx.doi.org/10.1007/s00521-004-0411-6.

[98] Erdem Simsek et al. “Influence of particle diameter and material properties on mixing of monodisperse spheres on a grate: Experiments and discrete element simulation”. In: *Powder Technology* 221.0 (May 2012), pp. 144–154.

[99] U. Sindel and I. Zimmermann. “Measurement of interaction forces between individual powder particles using an atomic force microscope”. In: *Powder Technology* 117.3 (2001), pp. 247–254.

[100] Dale M. Snider. “Three fundamental granular flow experiments and CPFD predictions”. In: *Powder Technology* 176.1 (2007), pp. 36–46.

[101] R. Sondergaard, K. Chaney, and C. E. Brennen. "Measurements of Solid Spheres Bouncing Off Flat Plates". In: *Journal of Applied Mechanics* 112.3 (1990), p. 694. URL: http://resolver.caltech.edu/CaltechAUTHORS:SONjam90.

[102] Jin Sun and Sankaran Sundaresan. "Radial hopper flow prediction using a constitutive model with microstructure evolution". In: *Powder Technology* 242.0 (July 2013), pp. 81–85.

[103] K. Takenaka et al. "Shape Effects of the Yield Locus on the Rankine Coefficient". In: *Advanced Powder Technology* 19.1 (2008), pp. 25–37.

[104] Gabriel I. Tardos. "A fluid mechanistic approach to slow, frictional flow of powders". In: *Powder Technology* 92.1 (June 1997), pp. 61–74.

[105] Jose' M. Torralba et al. "Development of high performance powder metallurgy steels by high-energy milling". In: *Advanced Powder Technology* 24.5 (Sept. 2013), pp. 813–817.

[106] B. Vaferi et al. "Artificial neural network approach for prediction of thermal behavior of nanofluids flowing through circular tubes". In: *Powder Technology* 267.0 (Nov. 2014), pp. 1–10.

[107] Temel Varol, Aykut Canakci, and Sukru Ozsahin. "Artificial neural network modeling to effect of reinforcement properties on the physical and mechanical properties of Al2024-B4C composites produced by powder metallurgy". In: *Composites Part B: Engineering* 54.0 (Nov. 2013), pp. 224–233.

[108] Loc Vu-Quoc and Xiang Zhang. "An accurate and efficient tangential force-displacement model for elastic frictional contact in particle-flow simulations". In: *Mechanics of Materials* 31.4 (Apr. 1999), pp. 235–269.

[109] C. M. Wensrich and A. Katterfeld. "Rolling friction as a technique for modelling particle shape in DEM". In: *Powder Technology* 217.0 (Feb. 2012), pp. 409–417.

[110] C. M. Wensrich and A. Katterfeld. "Rolling friction as a technique for modelling particle shape in DEM". In: *Powder Technology* 217.0 (Feb. 2012), pp. 409–417.

[111] Wikipedia. *Discrete element method*. URL: http://en.wikipedia.org/wiki/Discrete_element_method.

[112] M. Wojcik, J. Tejchman, and G. G. Enstad. "Confined granular flow in silos with inserts - Full-scale experiments". In: *Powder Technology* 222.0 (May 2012), pp. 15–36.

[113] Hideto Yoshida et al. "Particle size measurement of reference particle candidates and uncertainty region of count and mass based cumulative distribution". In: *Advanced Powder Technology* 0 ().

[114] Y. C. Zhou et al. "An experimental and numerical study of the angle of repose of coarse spheres". In: *Powder Technology* 125.1 (2002), pp. 45–54.