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Estimation of product relating energy of wet operated stirred media mills in terms of process transfer to other mill geometries and sizes

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ABSTRACT

Wet grinding with stirred media mills is a wide distributed unit operation which occurs in many different industrial areas from milliliter to cubic meter scale. For different applications diverse rotor, stator and grinding media separation systems were developed. The transfer from one scale or mill type to another is a challenge in the process development. Scale-up rules for geometrically similar mills exist but reach fast their boundaries when changing the mill geometry. Besides the mill dependent values each material and particle size needs a certain breakage energy which is provided by colliding grinding media and which has to be considered for those transfer processes as well. Thus the transferred energy depends on the process parameters, the mill geometry and the formulation of the suspension including material and rheological parameters. The introduced energy is reduced to a product relating amount. This product relating energy can be optimized following the stress model, thus an estimation of optimum process parameters for different geometries and materials is possible which offers the chance to transfer processes in an energetically efficient way with a low experimental effort.

1. Introduction

Wet milling in stirred media mills is, like many grinding processes an energy and time intensive process, especially if the desired product is in submicron or nanometer size range. Its transfer and scale-up or -down is challenging due to a wide range of adoptable process parameters, selectable mill geometries and formulation requirements. Hence the amount of experiments due to setup a new process, to scale or optimize a known process or to generate material parameters of a new feed product is high and should be decreased to the lowest necessary amount.

The energy introduced to the mill dissipates to a huge amount into heat energy. The main part of energy dissipation is taking place for processes which are not included to breakage events of particles, like friction at of grinding media with grinding chamber walls or with each other, friction and movement of suspension or elastic deformation of grinding media (Stender et al., 2004). Thus the different amounts are in functional connection with the mill geometry, suspension and the process parameter. Much literature is found relating to the connection of breakage results to process or mill parameters realized e.g. with PBM-Methods (Bilgili and Scarlett, 2005a, 2005b; Eksi et al., 2011; Hennart et al., 2009). These types of model are taking the stirred media mill as black box and correlate grinding results with process parameter for certain products or mills. A physical based model for predicting grinding processes is not reported in these literature sources. For the understanding of processes taking place in stirred media mills, it is necessary to get information about the grinding media movement inside the grinding chamber as function of process and suspension parameters. Therefore two different approaches are known with the target to predict grinding media velocities inside the mill for calculation of collision energies.

One approach bases on the coupling of the fluid flow behavior inside the grinding chamber with the power consumption of the mill. In this case the grinding media were considered to be a part of the introduced suspension. The suspension is characterized by its flow behavior in combination with the occurring viscosities. Eskin et al. showed a microhydrodynamic model for stirred media mill, with the influence of different process parameters to predict movement and oscillation velocities of grinding media (Eskin et al., 2005). Radziszewski developed the so called shear-volume power to connect the power consumption with stirrer rotation number and viscosity of the suspension (Radziszewski, 2015). With that approach they achieved good predictability of measured and predicated power consumption for different vertical stirred media mills.

The model following Kwade and Stender used the results based on fluid flow observations as well (Blecher and Schwedes, 1996; Kwade, 2004; Theuerkauf and Schwedes, 1999, 2000). But in difference to the models described above they used the knowledge of

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Nomenclature

Symbols

A	surface area [m^2]
A_{Rotor}	rotor surface area [m^2]
C	fitting parameter [–]
c_m	mass related solids content [–]
c_V	volumetric solids content [–]
D	fitting parameter [–]
d_{GM}	grinding media diameter [m]
f_{mill}	mill constant [–]
E_m	specific energy [J/kg]
$E_{m,P}$	product relating specific energy [J/kg]
F	shear force [N]
m_P	product mass [kg]
N_{GM}	number of grinding media inside grinding chamber [–]
$n_{Stirrer}$	rotation number of the stirrer [1/s]
P	power [W]
P_0	idle power [W]
S_P	particles surface area [m^2]
$\overline{SE}_{GM}$	median stress energy of the grinding media [J]
$\overline{SE}_P$	median stress energy of the product [J]
SF_{GM}	stress frequency [1/s]
SN	stress number [–]
t_G	grinding time [s]
Δv	velocity gradient [m/s]
V_{GC}	grinding chamber volume [m^3]
V_P	particle volume [m^3]
v_t	stirrer tip speed [m/s]
V_W	water volume [m^3]
x_P	particle size [m]
Δy	distance [m]
ρ_{GM}	grinding media density [kg/m^3]
γ	shear rate [1/s]
η	viscosity [Pas]
τ	shear stress [Pa]
τ_L	shear stress of pure liquid [Pa]
v_e	energy transfer coefficient [–]
v_{Mill}	energy transfer coefficient of the mill [–]
$v_{Product}$	energy transfer coefficient of the product [–]
$v_{Suspension}$	energy transfer coefficient of the suspension [–]

the flow gradients between rotating and non-rotating mill elements to estimate grinding media velocities and with it the stress energy which takes the relative grinding media velocity into account. The stress energy is comparable with the kinetic energy of colliding grinding media. The sum of the stress energies resulting from all stress events leads to a product relating energy which is connected to the specific energy. The measurable specific energy values are reduced by different energy transfer coefficients to the product relating energy.

The stress frequency or number as well as the stress energy distribution are no direct measureable values. Thus to get a more detailed result current and future work will more and more give insights by DEM-simulations (Powell et al., 2011; Refahi et al., 2010; Sinnott et al., 2006). Yet, a coupling of DEM with CFD methods is possible but complicated rotating geometries in combination with great number of grinding media insight the mill are still challenging.

Within this work, the stress model known by Kwade (2003) and the enhanced version shown by Breitung-Faes and Kwade (2013, 2014) has been further developed. It enables the user to predict energetically optimized process parameters for different materials by the introduction of different material parameters to the stress model. The stress model itself was improved by taking the median stress energy into account, which is a reflecting value of the mill geometry. Thus, it is possible to predict optimized process parameters and to calculate the product relating specific energy, but the prediction of grinding time of specific energy was not possible yet. Within this paper to connection of the product relating energy with the measurable specific energy is discussed.

2. The stress energy model

Usually results of grinding experiments are expressed by product quality e.g. particle size x_P as function of measured specific energy input E_m, which is determined as:

$$E_m = \frac{\int (P - P_0) dt_G}{m_P} \tag{1}$$

For the calculation the measurement of the power input $(P–P_0)$ and the grinding time t_G are necessary as well as the knowledge of the product mass m_p. Following the stress model the specific energy E_m can be calculated by the sum of the stress number SN, the median stress energy $\overline{SE}_P$ divided by the product mass m_p and a so called energy transfer factor v_e which recognizes the energy dissipation due to energy transfer to the fluid (in terms of viscosity), elastic deformation of grinding media, displacement flows of the suspension between approaching grinding media, collisions without feed products and friction effects (Stender et al., 2004).

$$E_m \cdot v_e = E_{m,P} = \frac{SN \cdot \overline{SE}_P}{m_P} \tag{2}$$

Following Stender the energy transfer coefficient v_e is a product of different single energy transfer or dissipation coefficients (Stender et al., 2004). The product of the measured specific energy and the different energy transfer coefficients delivers the energy which is transferred to the product as Fig. 1 shows. Here different dissipation mechanisms are summarized, thus three different energy transfer coefficients are defined:

$$v_e = v_{Mill} \cdot v_{Suspension} \cdot v_{Product} \tag{3}$$

The mill related energy transfer coefficient represents the energy dissipation due to frictional elements of the mill e.g. at the grinding chamber wall. Here wet stirred media milling is the focus of this work, thus the friction of grinding media with the grinding chamber walls and each other under the operation with pure water was used to establish the value for $v_{Mill.}$ The energy transfer coefficient $v_{Suspension}$ represents the energy dissipation into the suspension due to increased viscosity in comparison to the pure liquid. At least the product related energy transfer coefficient $v_{Product}$ recognizes the deformation behavior of grinding media, due to the assumption that elastic deformation energy is not transferred to the particles to cause fractures. This term takes the solids concentration of the suspension as well into account because there with the number of stressed particles is recognized.

Relating to Kwade the mill related stress number SN is defined as product of grinding media contacts N_C within a certain grinding time t_G. The grinding media contact number of is proportional to the number of grinding media N_{GM} inside the grinding chamber, the revolution number of the stirrer $n_{Sitrrer}$ and the grinding time t_{GM} $[N_C \sim f(N_{GM}, n, t_G)]$ (Kwade and Schwedes, 2002).

$$SN \propto N_C \cdot t_G \tag{4}$$

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