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Sophie Schwarzwälder[1]
Roland Nied[2]
Hermann Sickel[1]

[1] NETZSCH-Condux Mahltechnik GmbH, Hanau/Wolfgang, Germany.

[2] Unternehmensberatung Dr. Roland Nied, Bonstetten, Germany.

Dry Fine Grinding with Jet Mills: Potentials of Energy Optimization

The interest in finer, dry products has led to the development of more efficient jet milling processes. The first part of the paper describes the thermodynamic basic principles for generation and application of steam, and compressed gases. Practical experience has shown that in the aspired fineness range stabilization during grinding provides an enormous potential for improvement. Some selected examples demonstrate that the energy requirement can be reduced by a factor of more than two by suitable choice of stabilizers.

Keywords: Dry grinding, Jet mill, Stabilizer

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1 Thermodynamics of Compression and Expansion of Ideal Gases

A jet mill is operated by compression and subsequent expansion of gas after the nozzles. These processes can be described by the theory of gas dynamics [1].

Assuming an adiabatic process, the total energy input is defined by:

$$E = \frac{m}{2} v_{\mathrm{ad}}^2 \tag{1}$$

For ideal gases, the jet velocity is given by:

$$v = \sqrt{2\frac{\kappa}{\kappa-1} R T_0 \left(1-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right)} \tag{2}$$

The operating expenditure with reversible adiabatic compression is calculated as:

$$A = \frac{\kappa}{\kappa-1} m R T_0 \left[\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}} - 1\right] \tag{3}$$

By introducing Eq. (2) in Eq. (1), the adiabatic energy becomes:

$$E_{\mathrm{ad}} = \frac{\kappa}{\kappa-1} m R T_0 \left[1-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right] \tag{4}$$

The theoretical efficiency degree can be determined by:

$$\eta_{\mathrm{theor.}} = \frac{E_{\mathrm{ad}}}{A} \tag{5}$$

There are three case studies. First case: compression in the low-pressure range by a single-stage compressor up to 4.5 bar (absolute) with utilization of waste heat.

$$\frac{T_1}{T_0} = \left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}} \tag{6}$$

The result for the theoretical efficiency degree is 1.

Second case: Gas is compressed in the high-pressure range (double-stage compressor up to 11.5 bar (absolute)) with utilization of waste heat from the second stage.

$$\eta_{\mathrm{theor.}} = \left[\frac{1-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{2\cdot\kappa}}}{\left(\frac{p_0}{p_1}\right)^{\frac{\kappa-1}{2\cdot\kappa}} - 1}\right] \tag{7}$$

An identical compression ratio in both stages is assumed.

Third case: Compression in the high-pressure range without utilization of waste heat.

$$\eta_{\mathrm{theor.}} = \left[\frac{1-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{2\cdot\kappa}}}{1-\left(\frac{p_0}{p_1}\right)^{\frac{\kappa-1}{2\cdot\kappa}}}\right]^2 \tag{8}$$

The degree of efficiency for the double-stage compressor is obtained from the product of the corresponding degree of efficiency of the individual steps. Fig. 1 illustrates the theoretical

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Correspondence: Sophie Schwarzwälder (sophie.schwarzwaelder@netzsch.com), NETZSCH-Condux Mahltechnik GmbH, Rodenbacher Chaussee 1, 63457 Hanau/Wolfgang, Germany.

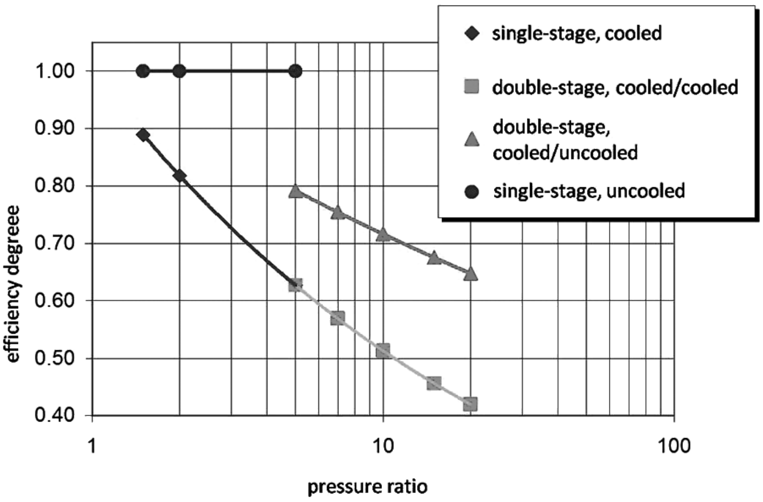


Figure 1. Efficiency degree $\eta_{theor.}$ of the ideal compressor for air compression as a function of the pressure ratio p_0/p_1.

degree of efficiency for the discussed types of compressors depending on the pressure ratio p_0/p_1.

2 Generation and Utilization of Steam

For generation of dry steam, conditioned compressed water is in the first step vaporized. Then, this saturated steam is superheated and available in the next step in a dry state for the grinding process. The thermodynamic data of steam can be taken from a steam table or read from the *h*-*s*-diagram (Fig. 2).

As an example, a steam jet mill can be operated at 40 bar (absolute) and 350 °C (inlet enthalpy ~ 3100 kJ kg^{-1}). If no external work is dissipated, the process can be described as adiabatic. After expansion in the mill (pressure 1.1 bar (absolute), $T = 300$ °C) the steam enthalpy decreases to 2400 kJ kg^{-1}. The enthalpy reaches its original value in the end, which results in a temperature of ~ 300 °C.

The difference between inlet enthalpy and expanded enthalpy (approximately 700 kJ kg^{-1}) is the useful enthalpy difference. It characterizes the useable adiabatic energy:

$$E_{ad} = m\Delta h \tag{9}$$

The ideal degree of efficiency for the generation of steam results from:

$$\eta_{theor.} = \frac{\Delta h}{h_0} \tag{10}$$

Fig. 3 indicates the ideal degree of efficiency of steam, increasing with higher steam pressure.

3 Practical Efficiency with Comparison of Both Systems

The practical degree of efficiency for the compression of gases deviates from the ideal degree of efficiency. Essential reasons are the gap leakage as well as the loss of heat and the mechanical leakage of compressors. Therefore, manufacturer data from Atlas Copco and Aerzener have been evaluated. As an example, Fig. 4 displays the adiabatic energy input increasing with higher power at the driving shaft for a single-stage compression at 4.5 bar (absolute).

The evaluated result is a degree of efficiency of adiabatic jet energy opposed to the electrical shaft power (Tab. 1).

To compare both systems gas and steam, it is necessary to consider the primary energy. The generation of electricity subject to the primary energy requirement is carried out in Germany with an average degree of efficiency of about 36 % [2].

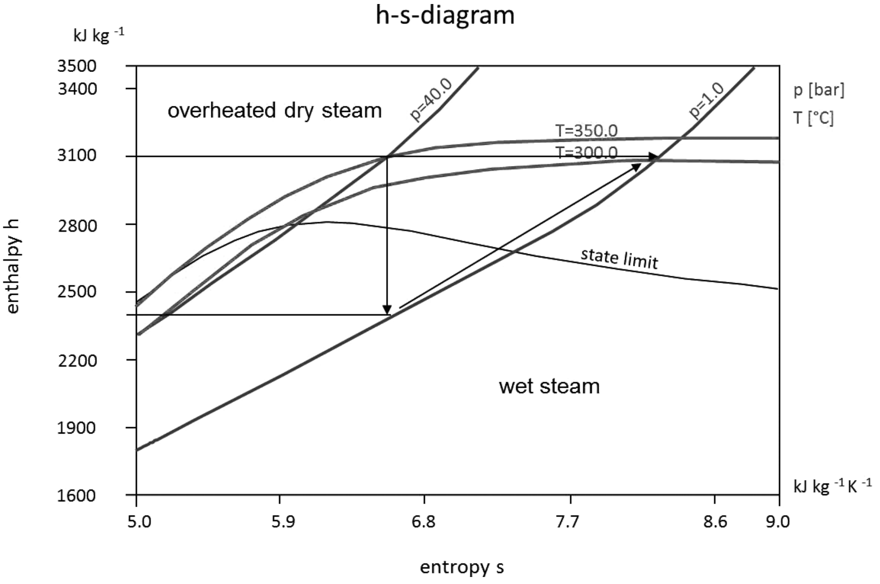


Figure 2. *h*-*s*-Diagram of steam.

The thermal efficiency of a steam generator (average of boiler and superheater) is ~ 90 %. The resulting overall efficiency degree from primary energy to useable adiabatic energy is given in Tab. 2.

4 Particle Breakage in Impact Grinding

As demonstrated in Fig. 5, energy efficiency is a function of strain rate and stress speed when brittle materials are milled through impact. For the individual impact, three areas can be distinguished. Regarding energy requirement and the achievable fineness,

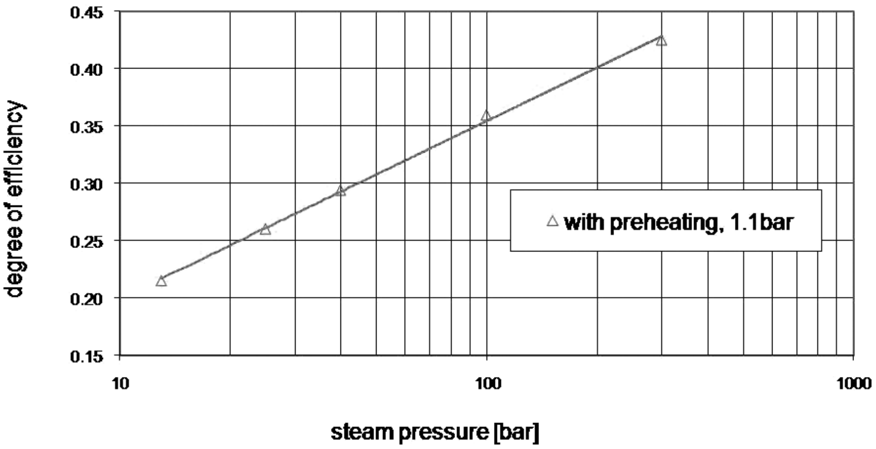


Figure 3. Ideal degree of efficiency of steam generation dependent on pressure; with preheated feed water, flash pressure 1.1 bar (absolute).

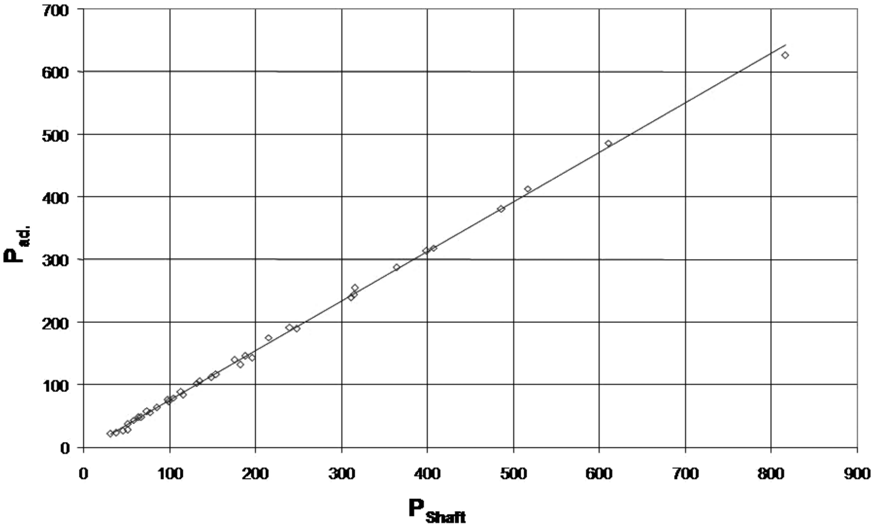


Figure 4. Adiabatic jet energy ($P_{ad.}$) depending on the electrical shaft power (P_{Shaft}) of a single-stage compressor (Aerzener).

Table 1. Resulting degree of adiabatic jet energy as opposed to electrical shaft power.

Type of compressor	Degree of adiabatic jet capacity
Single-stage, uncooled (4.5 bar (abs), 220 °C)	~ 77 %
Double-stage, stage 2 uncooled (11 bar (abs), 150 °C)	~ 62 %
Double-stage, cooled (11 bar (abs), 25 °C)	~ 45 %

there is an optimum depending on stress speed and stress energy [3].

Tab. 3 indicates that the outlet speed of an expanded steam jet from a nozzle is almost twice as high (1161 m s^{-1}) as that of air (541 m s^{-1}). It can be expected that the higher (discrete) kinetic energy leads to more powerful particle impacting and consequently to a finer final grinding. Thus, the specific jet energy, i.e., the global energy input of steam (0.19 kWh kg^{-1} grinding media), is approximately four times higher than that of air (0.041 kWh kg^{-1} grinding media). If the volume flow and energy requirement are the same, it can be assumed that the throughput will increase by the same factor.

5 Experimental Results

For the grinding experiments, a jet mill CGS 50 (Fig. 6) of NETZSCH-Condux with a nominal air flow rate of 1000 m^{3}h^{-1} and an installed power of approximately 35–50 kW was used. For steam operation, an s-Jet 500 system of NETZSCH-Condux with a nominal steam consumption of 500 kg h^{-1} and an installed power of approximately 80–120 kW was provided. The particle size distribution was determined by laser diffraction using Cilas 1064.

The ability to maximize energy efficiency is dependent on stress speed and specific energy input [3].

For high-pressure air (cold), the jet exit velocity and specific jet energy is almost the same as for low-pressure air (hot) (Tab. 3). According to Schönert [3] the stress on particles is identical if the energy input is equal. Therefore, the particle size related to the energy requirement is similar for both gas processes (Fig. 7). As the generation of low-pressure air (hot) results in a higher degree of efficiency, this process is to be favored.

Steam as grinding media provides an approximately two times higher jet exit velocity than gas (Tab. 3). In this case, the increased stress [4] leads to finer particles (Fig. 8).

Table 2. Resulting overall efficiency degree from primary energy to adiabatic energy.

Type of compressor	Overall efficiency degree
Single-stage, non-cooled (4.5 bar (abs), 220 °C)	~ 28 %
Double-stage, stage 2 non-cooled (11.5 bar (abs), 150 °C)	~ 22 %
Steam, 100 bar, 400 °C	~ 32 %
Steam, 40 bar, 320 °C	~ 26 %

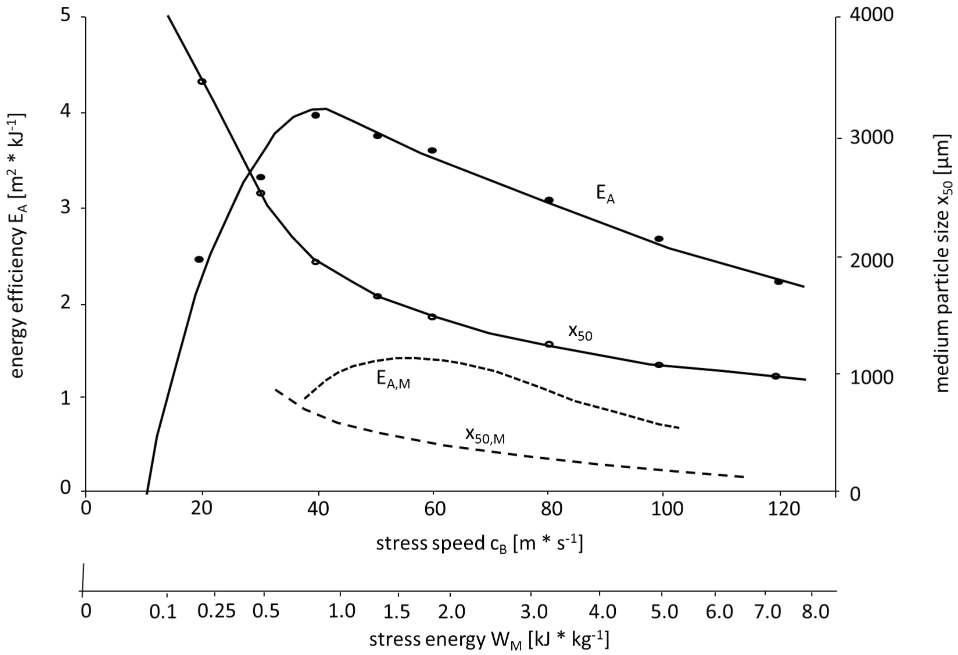


Figure 5. Energy efficiency as a function of strain rate according to Landwehr [4].

Table 3. Comparison of the most important parameters of gas and steam.

	Air		Steam	
	11 bar (abs), 20 °C	4.5 bar (abs), 220 °C	40 bar (abs), 320 °C	100 bar (abs), 400 °C
Jet exit velocity [m s⁻¹]	541	588	1161	1303
Specific jet energy [kWh kg⁻¹]	0.041	0.048	0.19	0.24

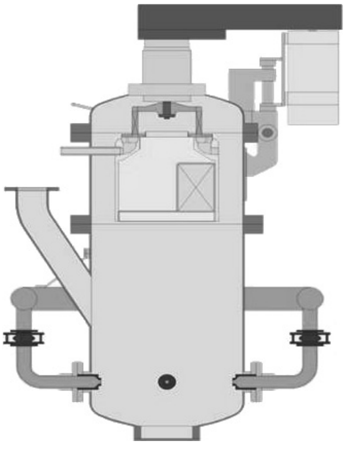


Figure 6. Scheme of a NETZSCH-Condux CGS.

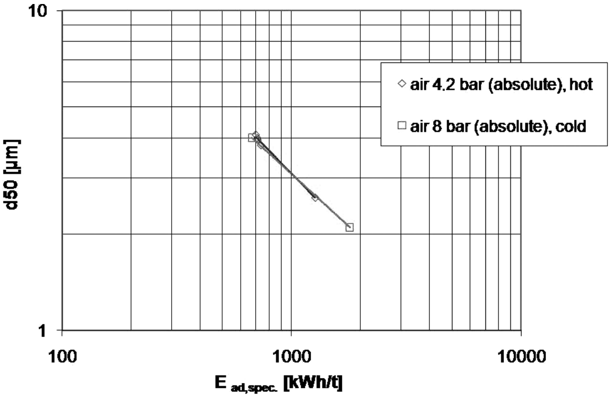
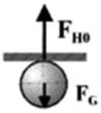


Figure 7. Comparison of grinding graphite with low-pressure hot air and high-pressure cold air.

6 Effect of Grinding Aids on Energy Requirement and Throughput

The finer the particles, the more they tend to agglomerate. This is a problem during grinding down to finenesses of a d_{50} below 2 µm. Reasons are the surface forces of particles, which become stronger with the second power, as well as the mass forces, which increase with the third power. In particular, the van der Waals and the electrostatic forces act as surface forces. The van der Waals forces depend on the size of and distance between the particles, their surface roughness, surface hardness, and on the adsorption layers. These parameters impede an evaluation of the adhesive forces of fine powders. An approximation is given in Tab. 4.

Table 4. Approximate evaluation of the adhesive forces (adhesive force ratios) of fine to nano-scale particles [6].

Physical active principle	Particle diameter d [µm]	F_{vdW} / F_G	Evaluation
	10–100	1–100	Slightly adhesive
	1–10	$100–10^4$	Adhesive
	0.01–1	$10^4–10^8$	Very adhesive

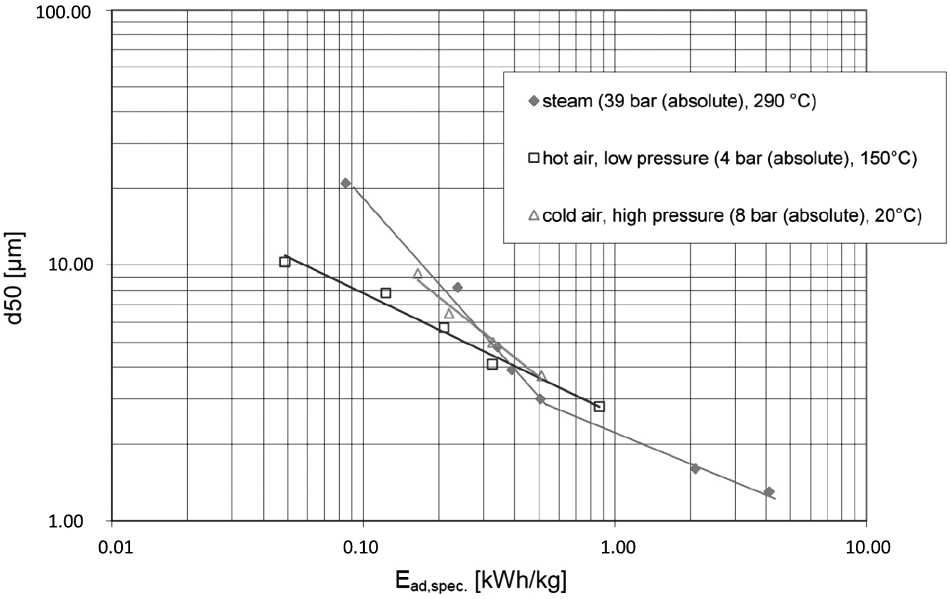


Figure 8. Grinding of talcum with steam, hot air, and cold air.

Contact and friction can cause particles to become electrostatically charged. Particles which are electrostatically charged to different extents attract each other (Coulomb forces). Due to this fact, the classifier identifies agglomerates and no longer individual particles. The throughput of the mill decreases and the product quality and product characteristics are influenced in a negative manner. Godet-Morand [6] already reviewed the action of grinding aids during talc grinding in an opposed air jet mill and showed that stabilizing of the particles has a positive effect on throughput. For the stabilizing experiments different types of additives (wet and dry) were used.

Fig. 9 illustrates the dependence of the adiabatic energy requirement on the amount of additive added, using the example of hydraulic bonding agent grinding. In this case, it is clear that the energy requirement decreases with the increase of the percentage of additive applied. When 2.5 % of additive is added, the energy requirement decreases by around two thirds (750 kWh t^{-1}) compared to the amount required without additive (2300 kWh t^{-1}).

Fig. 10 presents the deviated throughput of a hydraulic bonding agent when grinding with four different additives. Depending on the additive used, the product throughput varies, although all other conditions are identical. With additive D an increase of around 40 % was recorded compared to B (100 %), whereas A with only 80 % caused a decrease in throughput.

Tab. 5 summarizes the effects of the use of additives with examples of three different products. For every listed product, the throughput increases for the same particle size (d_{50}), while the specific adiabatic energy requirement decreases by the same factor. For the ceramic pigment, this factor is even 6.0.

7 Conclusions

The application of single-stage, uncooled low-pressure compressors for jet milling at pressures lower than 4.5 bar (absolute) and temperatures above 200 °C offers an economical alternative to double-stage, cooled compressors in the coarser range ($d_{50} > 2–3$ µm). By using the heat, costs for utilities can be reduced and, therefore, energy costs saved.

The operating medium superheated steam is opening new doors for the dry production of particle sizes in the submicrometer range. The use of steam allowed obtaining finer particles in the grinding process. Due to the higher total energy input into the mill, steam can also be used for coarser grinding finenesses with a significant increase of throughput.

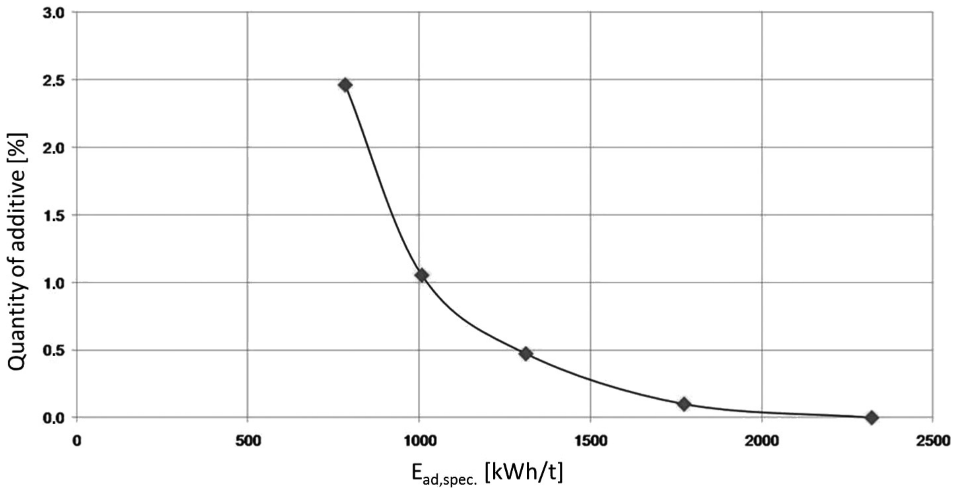


Figure 9. Adiabatic energy requirement for the grinding of hydraulic bonding agent depending on the amount of additive, $d_{50} = 1.7$ µm.

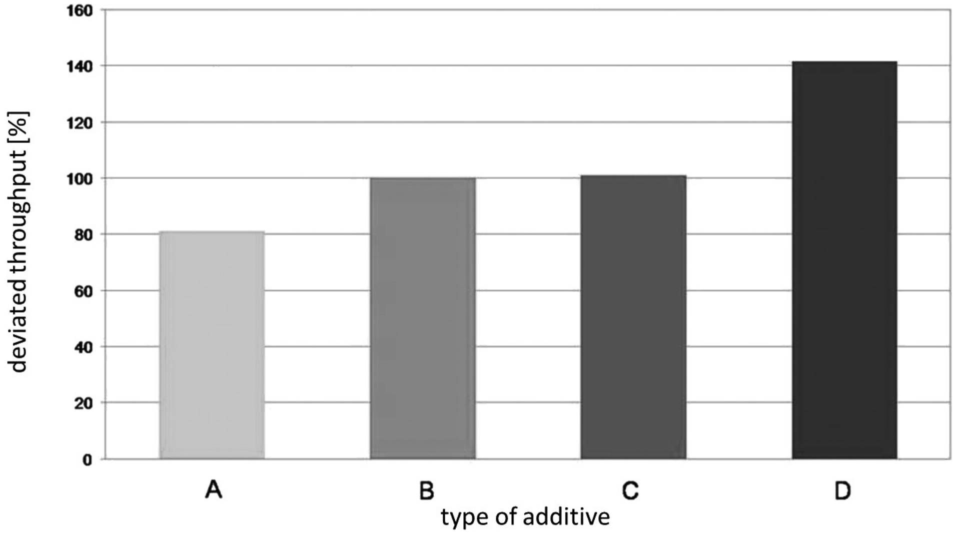


Figure 10. Deviated throughput of a hydraulic bonding agent depending on the type of additive, $d_{50} = 1.7$ µm.

Table 5. Examples of stabilization applications.

Product	d_{50} [µm]	Throughput [kg h^{-1}]	$E_{ad,spec.}$ [kWh kg^{-1}]	Additive
Ceramic pigment	0.75	21.2	2.23	Without
	0.79	128.4	0.37	With
Metal oxide	0.66	38.9	1.21	Without
	0.89	140.6	0.34	With
Hydraulic bonding agent	3.18	11.5	8.13	Without
	2.98	27	3.44	With

In the ultrafine area (d_{50} less than 2 µm), particles have a tendency to agglomerate due to increasing surface forces. A suitable stabilization by means of additives during the grinding process improves the throughput and at the same time the energy requirements are reduced.

The authors have declared no conflict of interest.

Symbols used

A	[J]	expenditure
c_B	[m s^{-1}]	stress speed
d_{50}	[µm]	volume median size
E	[J]	energy
E_{ad}	[kWh]	adiabatic energy
$E_{ad,\ spec.}$	[kWh]	specific adiabatic energy demand
F_G	[kg m s^{-2}]	gravity force
F_{vdW}	[kJ mol^{-1}]	van der Waals force
Δh	[kJ kg^{-1}]	enthalpy differential
h_0	[kJ kg^{-1}]	enthalpy at mill entry
κ	[–]	isentropic exponent
m	[kg]	mass
p_0	[N m^{-2}]	entry pressure
p_1	[N m^{-2}]	final pressure
R	[J kg^{-1}K^{-1}]	gas constant
T_0	[K]	entry temperature
v	[m s^{-1}]	velocity
W_M	[kJ kg^{-1}]	stress energy
x_{50}	[µm]	medium particle size
$\eta_{theor.}$	[–]	theoretical efficiency degree
ρ_c	[kg m^{-3}]	continuous density

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