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ADVANCED STUDIES ON COAL INJECTION INTO A CAVITATION CELL FOR THE PURPOSE OF COMMINUTION

BADANIA PROCESU WTŁACZANIA WĘGLA DO KOMÓR KAWITACYJNYCH W CELU ROZDRABNIANIA

In this study, the effect of coal comminution with waterjets enhanced by cavitation was investigated. The experiments were carried out using mono-size coal feeds in a batch closed circuit, in a specially designed cell to induce cavitation at 69 MPa inlet pressure and back pressures of zero and 0.345 MPa. Test results were evaluated on the product calculated surface area and the Rosin-Rammler parameters. The experiments showed that the maximum particle size reduction was achieved during the first run through the comminution circuit operated without back pressure. However, a decreasing tendency in comminution efficiency was noted with the number of runs through the system. The use of 0.345 MPa back pressure resulted in a wider size distribution of the product.

Keywords: waterjet, coal, comminution, Rosin-Rammler plots

W pracy przedstawiono badanie procesu rozdrabniania węgla przy pomocy dysz wodnych, wspomaganego przez kawitację. Eksperymenty prowadzono na partiach brył węgla o jednakowych rozmiarach, w układzie zamkniętym, w specjalnej komorze kawitacyjnej przystosowanej do działania przy ciśnieniu wlotowym 69 MPa i przy przeciwciśnieniu zero i 0.345 MPa. Wyniki eksperymentu określono na podstawie obliczeń pól powierzchni, przy wykorzystaniu parametrów Rosina-Rammlera. Eksperymenty wykazały, że maksymalną redukcję rozmiarów ziaren węglowych uzyskuje się w trakcie pierwszej próby dokonanej w komorze bez zastosowania przeciwciśnienia. Z każdym kolejnym przebiegiem obserwowano malejącą skuteczność rozdrabniania. Zastosowanie przeciwciśnienia rzędu 0.345 MPa spowodowało większy rozrzut wymiarów ziaren w produkcie końcowym.

Słowa kluczowe: struga wody, węgiel, rozdrabnianie, wykresy Rosina-Rammlera

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1. Introduction

Since ultra-fine grinding requires very large amounts of energy, the quest continues for new, more energy efficient comminution methods. Fragmentation of minerals through the development of compressive stresses within the mineral is not economical when compared to the benefits derived from inducing failure under tensile stresses. This fact was not utilized until high-pressure waterjets were applied for the purpose of coal slurry preparation. It has to be noted that waterjets were successfully used in mining applications (Kotwica, 1998; Kalukiewicz, 2003) and the use of waterjets is sought in comminution.

In the conventional method of abrasive injection for the purpose of cutting with abrasive waterjets, the energy contained in the accelerated high pressure jet stream is used to create a suction which draws abrasive into the jet within a special mixing chamber. Within this chamber the abrasive particles, still moving at a relatively low velocity, are impacted by the high speed waterjet and accelerated as the particle is moving down through the chamber and out along the collimating nozzle. Galecki and Mazurkiewicz (1987) noted that most of the abrasive particles fracture during the mixing and acceleration process in waterjets when they performed research on abrasive waterjet cutting heads. Milling effect studies have shown that up to 80% of the feed abrasive particles are broken into smaller sizes in the passage through the mixing chamber (Galecki et al., 1987). This is a highly undesirable effect during the abrasive particles acceleration process. However, this can be viewed as a new mechanism for particle size reduction (Galecki & Summers, 2000; Galecki, 2002). Research performed on abrasive waterjet cutting heads was an inspiration for the design of a waterjet based mill (Galecki & Mazurkiewicz, 1988).

High-pressure water jet comminution of coal (HPWJC) was first performed in 1986 by Galecki and Mazurkiewicz. Since comminution by waterjets was viewed as a new and very promising method for particle size reduction, soon many researchers adopted it as an interesting research topic and presented their views on the subject. Their studies contributed to advancing this new grinding method, which provides very unique properties of the product that were previously unobtainable. Comminution mechanism by waterjets is a very complex phenomenon, and there is no uniform view on it. As presented in these studies, fragmentation by waterjets is the combined effects of rapid dynamic shear stress developed by high velocity particle movement, cavitation bubble growth and collapse, direct impact of particles against a rigid target, water-edge effect, water-hammer effect, and particle/particle interaction effect (Zonghao & Zhinan, 2005; Cui et al., 2006, 2007; Guo & Dong 2007; Hlavac et al., 2010).

In this study, coal samples were ground by using a specially designed laboratory scale waterjet mill, to enhance the effect of coal comminution and the jet leaving the collimating nozzle was directed into a cavitation chamber, Figure 1. Batch type closed circuit grinding was applied to determine the size distribution change in each step. The results were evaluated using calculated surface area, Rosin-Rammler size and distribution parameters.

2. Materials and methods

A bituminous coal sample with 2.83% ash and 74.4 Hardgrove grindability index value was used in the study. The properties of the sample are presented in Table 1. It was crushed below 0.850 micron by applying a two-stage crushing process using a jaw crusher and a hammer mill.

The crushed material was subjected to riffling, coning and quartering processes. The samples were then dry sieved to produce mono-size samples to use in the stepwise grinding tests.

TABLE 1

Properties of bituminous coal sample

Proximate Analysis (% dry)		**Ultimate Analysis, (% dry)**	
Volatile Matter	28.42	Carbon	84.32
Ash	2.83	Hydrogen	4.86
Fixed Carbon	68.75	Nitrogen	1.62
Sulfur Content, (% dry)	0.82	Oxygen (by difference)	5.55
Calorific Value, (Btu/lb,dry)	14,635	Sulfur	0.82
Hardgrove grindability index	74.4	Ash	2.83

A Microtrac S3500 series particle size analyzer was used for the size distribution analysis. The results were evaluated by using a MATLAB® tool for plotting Rosin-Rammler diagram (Brezani & Zelenak, 2010). Nonlinear equation fitting routine was chosen for curve fitting in least square sense.

$$R(d) = 100 \cdot e^{-\left(\frac{d}{d''}\right)^{n}} \tag{1}$$

Please note that the Rosin-Rammler parameter *d”*, also known as size parameter, is the particle size at which 36.78% of the sample is coarser than *d”*. The parameter *n* is an indication of the breadth of the particle size distribution (Rosin & Rammler, 1933). The sample codes and the summary of feed particle properties are given in Table 2.

TABLE 2

Summary of the particle size distribution data of mono-size samples

Sample Code	**Size parameter, *d”* (micron)**	**Distribution parameter, *n***	**Correlation**	**Calculated surface area (M^2/CC)**
FR1	105.02	1.9956	0.99912	0.1050
FR2	180.77	2.9412	0.99912	0.0500
FR3	289.02	4.6891	0.99840	0.0236
FR4	408.43	4.7527	0.99650	0.0164

Tests were carried out using a conventional abrasive cutting head coupled with a specially designed cavitation cell. Details of this setup are given in Table 3. To carry out the experiments, the upstream pressure of 69 MPa was maintained. The feed mass flow rate was kept constant at 2 g/s during experiments and 200 g of each material was subjected to grinding. The cell was operated by applying zero and 0.345 MPa back pressure. Mono-size samples were subjected to batch-stepwise closed circuit grinding experiments in four loops. Slurry samples were taken after each step and ground products were filtered and dried prior to use in the following step.

Fig. 1. Cavitation cell

TABLE 3

Cutting head/cavitation setup characteristics

Orifice diameter	0.25 mm
Mixing tube length	76.2 mm
Mixing tube diameter	0.762 mm
Cavitation cell ID	76.2
Cavitation cell length	100 mm
Standoff distance	19 mm
Anvil (carbide) dimensions	19 mm × 19 mm

3. Results and discussions

Table 4 and Table 5 present the results of grinding in terms of Rosin-Rammler parameters. These results are accompanied by calculated surface areas which are used for process efficiency evaluation. From data analysis, it was found that the most significant size reduction was obtained during the first run throughout the cavitation cell. In parallel to that, higher size reductions were obtained for coarser feed sizes. These effects were more remarkable for the tests carried out without back pressure.

Data from Table 4 and 5 were used to visualize the relationship between the product size parameters and number of grinding steps in processing. This is depicted in Figure 2 and Figure 3. As it can be seen from these figures, the size parameters were significantly decreased after the first step of comminution. After that, the effect of size reduction is diminishing during the consecutive grinding steps. This is due to the use of finer feed in each further step of comminution. Based on these findings, it can be concluded that the product size parameter shows strong dependence on the feed size parameter.

TABLE 4

Particle size distribution data of products obtained using zero back-pressure

Feed Sample	**Steps**	**Size parameter, *d*” (micron)**	**Distribution parameter, *n***	**Correlation number**	**Calculated surface area (M^2/CC)**
FR1	Step 1	46.84	1.3531	0.99985	0.303
	Step 2	32.26	1.3888	0.99983	0.445
	Step 3	26.24	1.2459	0.99989	0.698
	Step 4	18.27	1.1120	0.99989	1.079
FR2	Step 1	63.70	1.2477	0.99982	0.247
	Step 2	36.78	1.3146	0.99984	0.408
	Step 3	29.78	1.2469	0.99983	0.571
	Step 4	23.15	1.1036	0.99982	0.823
FR3	Step 1	70.99	1.1826	0.99932	0.238
	Step 2	41.11	1.2255	0.99971	0.390
	Step 3	32.18	1.1702	0.99966	0.552
	Step 4	23.68	1.1432	0.99980	0.804
FR4	Step 1	82.17	1.1152	0.99974	0.224
	Step 2	51.59	1.3120	0.99964	0.271
	Step 3	37.92	1.3379	0.99962	0.374
	Step 4	25.88	1.1609	0.99981	0.721

TABLE 5

Particle size distribution data of products obtained using 0.345 MPa back-pressure

Feed Sample	**Steps**	**Size parameter, *d*” (micron)**	**Distribution parameter, *n***	**Correlation number**	**Calculated surface area (M^2/CC)**
FR1	Step 1	87.87	1.6954	0.99942	0.137
	Step 2	66.40	1.3169	0.99978	0.226
	Step 3	58.15	1.2069	0.99982	0.292
	Step 4	36.40	1.0040	0.99982	0.671
FR2	Step 1	126.87	1.5866	0.9974	0.112
	Step 2	82.76	1.2869	0.99827	0.200
	Step 3	75.29	1.0808	0.9996	0.273
	Step 4	59.25	1.0431	0.99942	0.337
FR3	Step 1	183.66	1.6961	0.99758	0.076
	Step 2	145.12	1.4052	0.99835	0.105
	Step 3	99.30	1.1050	0.99865	0.195
	Step 4	77.89	0.9576	0.99895	0.310
FR4	Step 1	248.43	1.3554	0.99758	0.072
	Step 2	160.66	1.2720	0.99649	0.126
	Step 3	140.27	1.1100	0.99795	0.144
	Step 4	93.52	0.9792	0.99847	0.245

Coal comminution with waterjets is a very complex phenomenon affected by all of the parameters involved in the process. However, only some of these parameters were tested. As described earlier, the effect of feed size parameter has a significant influence on product size

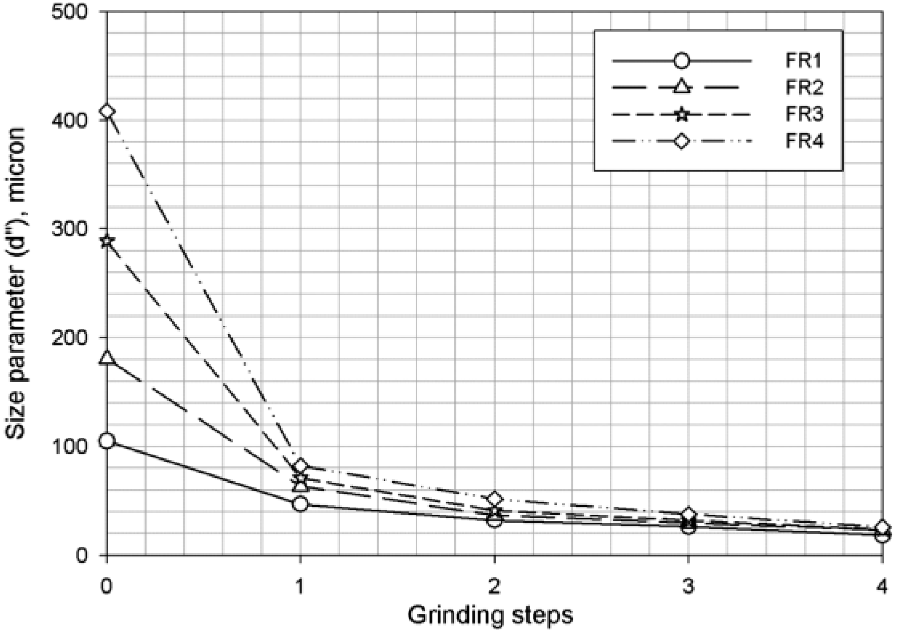

Fig. 2. Variations in product size parameters for different steps of grinding with zero back-pressure

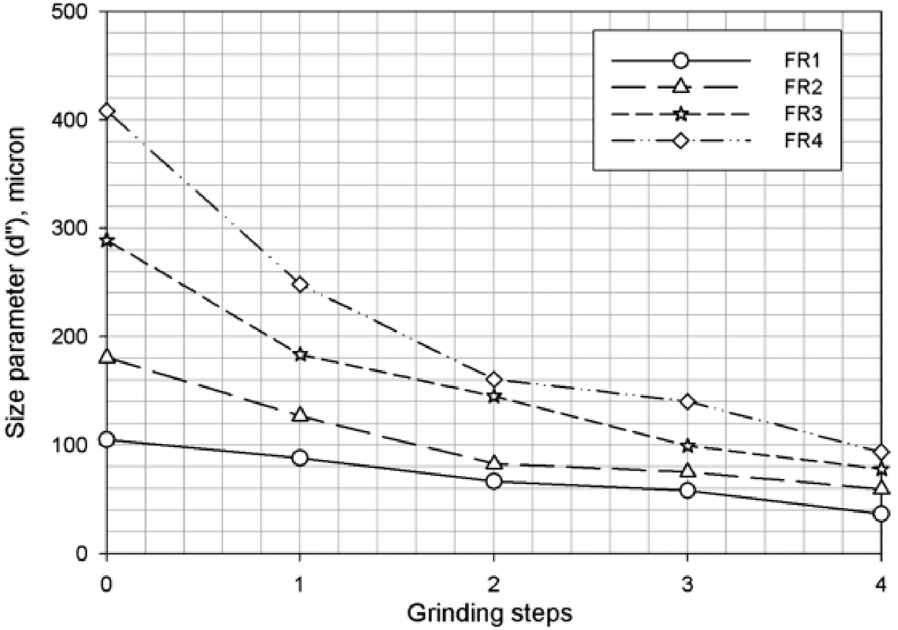

Fig. 3. Variations in product size parameters for different steps of grinding with 0.345 MPa back-pressure

parameter. The other parameter chosen for close analysis was back pressure maintained inside the cavitation cell. The effect of back pressure on product property can also be evaluated using again the plots in Figure 2 and 3. It becomes evident from these Figures that finer products were obtained for operating the cavitation cell without back pressure. Since the experiments were repeated three times, it can be stated with confidence that beyond step 2 in processing, product size parameters become very similar regardless of the initial feed size parameters.

The results obtained from the tests carried out using the cavitation cell with back-pressure of 0.345 MPa showed gradually decreasing size parameter (Figure 3). This is quite different behavior than that exhibited in Figure 2, with the coarser final product size parameters.

To characterize the particle size distribution of the products of comminution using Rosin-Rammler diagram, the distribution parameter *n* was analyzed. According to the interpretation by Rosin and Rammler, the lower number *n* parameter means the wider size distribution.

The relationship between the product distribution parameters and number of grinding steps in processing, with and without back pressure, are depicted in Figure 4 and Figure 5. It should be noted that the product size distribution parameters obtained after the first step of grinding are independent of the initial feed particle size and its distribution. This behavior remains unchanged throughout the consecutive grinding steps of comminution without back pressure.

Analysis of results of particle size distribution parameter for experiments using back pressure of 0.345 MPa led to a statement that particle size distribution is getting wider after each grinding step. This effect has to be analyzed in conjunction with the particle size reduction behavior as depicted in Figure 3.

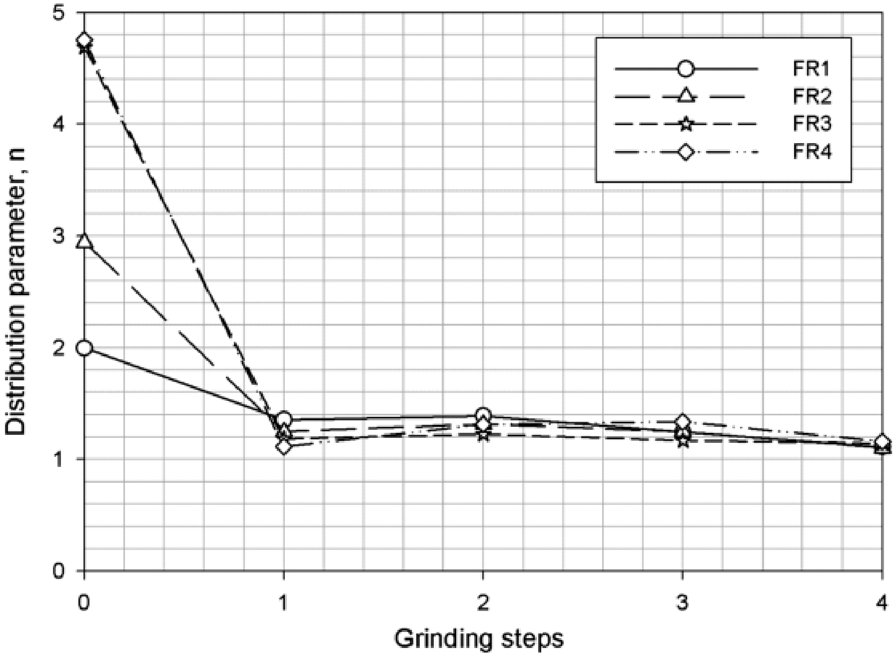

Fig. 4. Variations in distribution parameters for different steps of grinding with zero back-pressure

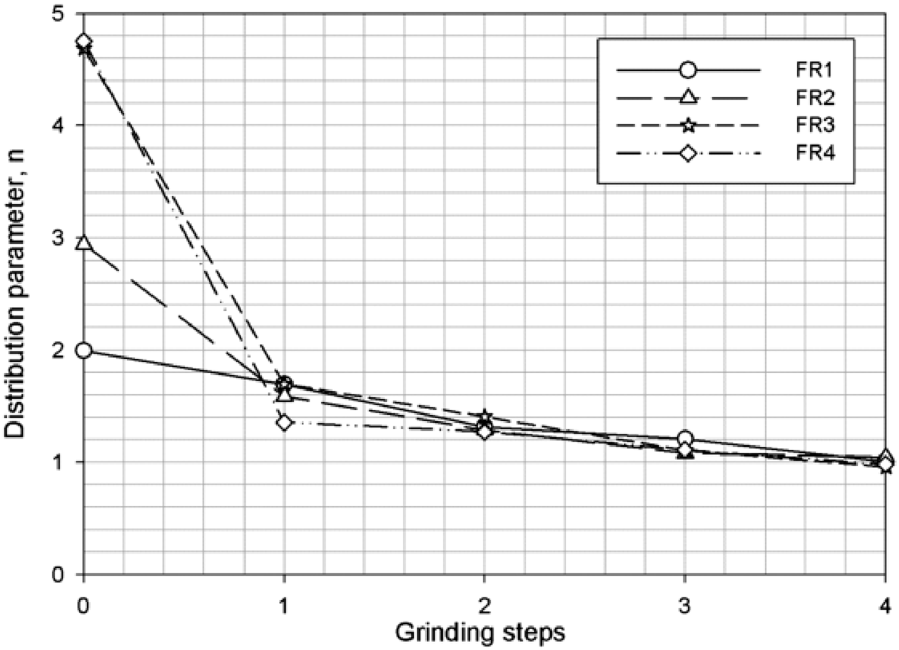

Fig. 5. Variations in distribution parameters for different steps of grinding with 0.345 MPa back-pressure

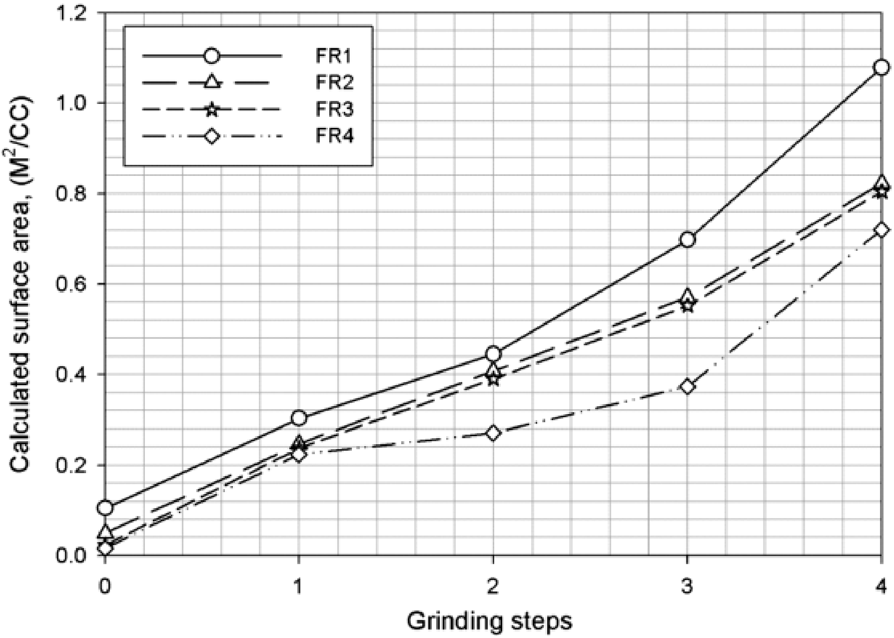

Fig. 6. Variations in calculated surface areas for different steps of grinding with zero back-pressure

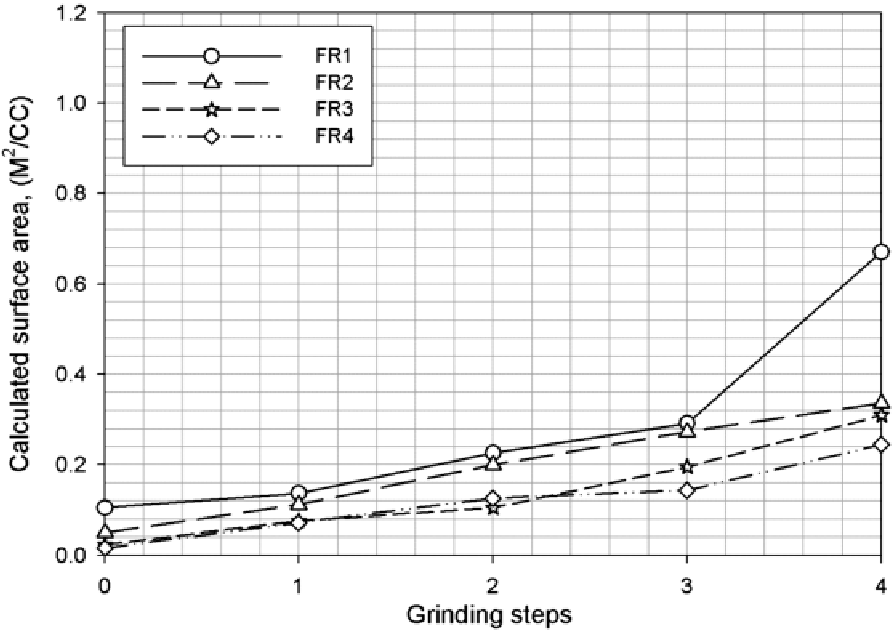

Fig. 7. Variations in calculated surface areas for different steps of grinding with 0.345 MPa back-pressure

According to the authors, using back pressure reduces the interaction of the particles with the anvil. However, this condition will increase the particle-particle interaction inside the mixing tube, resulting in increased abrasion between particles as a function of an increasing number of particles interacting in consecutive steps of grinding.

To fully characterize the comminution product properties, calculated surface areas were also analyzed and the results are given in Figure 6 and 7. The computation of this value was made under the assumption of that the particles are smooth, solid and in spherical form. These are the general assumptions used in particle size analysis equipment. Analyzing data presented in Figure 6 and 7 shows that an increased number of grinding steps resulted in an increased amount of fine particles, leading to the increased surface area. This tendency was observed for both test conditions.

4. Conclusion

The results presented in this paper are part of work towards coal comminution with waterjets. The research findings can be summarized as:

- In multi-step grinding, the maximum particle size reduction was achieved during the first runs through the cavitation cell for both conditions tested.
- Finer products were obtained for operating the cavitation cell without back pressure.

- With the use of back pressure, the multi-step grinding leads to slightly wider particle size distribution.
- For both test conditions, an increased number of grinding steps resulted in an increased amount of fine particles that translates to the increased surface area.

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