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تأثير معلمات التشغيل على تجفيف خام الدولوميت بواسطة طاقة الميكروويف

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الملخص

أجريت اختبارات التجفيف بواسطة الميكروويف على خام الدولوميت لتحديد تأثير معلمات التشغيل ومتغيراتها على آلية تجفيفة. تم تغذية خام الدولوميت، المسحوق بجسيمات ذات حجم 2 مم بالماء لجعل نسبة الرطوبة تصل حوالي 5 %، في فرن الميكروويف. تم تحديد معدل إزالة الرطوبة المعتمد على الوقت وتغيرات درجة حرارة السطح في التجارب التي أُجريت على أفران ميكروويف ذات قدرات مختلفة (180، 600 و 800 وات). تُعد القدرات المنخفضة للغاية لأفران الميكروويف الصناعية بمثابة عائق للأنشطة التي تتطلب قدرات عالية مثل التعدين. وتم أخذ معدل إزالة الرطوبة في الاعتبار عند تقييم النتائج. وأظهرت الظروف التجريبية المُثلى أنه يمكن إجراء عملية التجفيف عند 800 وات لمدة 8 دقائق ويتم فيها التخلص من 33 % من الرطوبة من معدن الدولوميت.

Impact of process parameters on drying of dolomite ore by microwave energy

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Abstract

Microwave drying tests on dolomite ore were carried out in order to determine the effect of process parameters and variables on its drying mechanism. Dolomite ore was crushed under 2 mm particle size with water to bring the moisture content to about 5% and then was fed into a microwave oven. The time-dependent moisture removal rate and surface temperature changes were determined at different microwave oven powers (180, 600 and 800W). The very low capacities of industrial microwave ovens are a handicap for activities requiring high capacities such as mining. The rate of moisture removal was taken into consideration in evaluating the results. The optimum experimental conditions for drying were carried out at 800W for 8 minutes. This results in the removal of 33% of the moisture from the dolomite ore.

Keywords: Dolomite; drying; microwave energy; moisture removal.

1. Introduction

Dolomite is a carbonate mineral formed by the partial or complete replacement of CaO with MgO from the structure of limestones (Temur, 2001). Dolomite ($CaMg(CO_3)_2$) contains 35% or more magnesium carbonate ($MgCO_3$) and has a density of 2.71 to 2.87 g/cm^3 depending on the MgO content. Its hardness ranges from 3.5 to 4 on the Mohs Scale. Depending on its physical and chemical structure, dolomite is used in the iron steel industry, glass, ceramics, paint, heat-insulation, building chemicals, agricultural land reclamation, and others. (Temur, 2001; DPT, 2008; MTA, 2016). The most important uses of dolomite are in the manufacturing of refractory materials and as flux (slagging) after being calcined in order to ensure that the impurities in steel production pass through to the slag (Kurt, 2010). In the glass industry, crude dolomite is used as a MgO source. Dolomite ore should contain at least 29.5% CaO and 21.4% MgO. At most, it will contain 0.6% insoluble matter, 0.25% Fe_2O_3, 0.4% Al_2O_3, 0.2% sulfate, 0.40% free carbon and a maximum of 0.10% moisture for glass industry applications (Kirikoglu, 1996).

The dolomite ore used in this study was processed for glass industry use and stored in an open stockpile. Dolomite ore may contain surface moisture depending on environmental factors, although it does not contain hygroscopic moisture. These environmental factors are seasonal precipitation, presence of water flow (pond, stream, canal, etc.), proximity to a mine site, and/or evaporation. The fact that all these factors affect the ore is the absence of an indoor stock area of the company. For this reason, it is compulsory to dry the stocked ore prior to industrial usage. Moisture evacuation in the industry is provided by evaporation using conventional, infrared and microwave heating (Tranquilla, 1997; Haque, 1999; Kingman, 1999).

Microwave energy is an alternative to conventional thermal treatment methods. It is an advancement in technology that can provide economic and environmental advantages to increase the commercial value of materials. Microwaves are non-ionizing electromagnetic waves covering a certain fraction of the electromagnetic spectrum in the frequency range of 300 Mhz to 300 Ghz and with a wavelength range from 1 mm to 1 m (Jones, 2004). Industrial microwaves have many applications. They are used in mining, agriculture and food, chemistry and pharmaceutical industries (Rinkevicha *et al.*, 2014). In mineral processing, the microwave energy benefited from in heating, drying, carbothermic reduction of oxide minerals, leaching, grinding, annealing and metal recovery. Microwave-assisted operations are also generally faster, cleaner and more economical than conventional methods (Kingman *et al.*, 1999; Haque, 1999).

The microwave energy drying mechanism is completely different from conventional drying. In conventional drying, heat is transferred to the surface of the material by conduction, transport or diffusion mechanisms, in which only conduction plays a role in heat transfer through the material. In conventional heating, the process is limited to the amount of heat flow from the surface to the material body, which is determined by the specific heat, thermal conductivity, density and fluidity of the material itself. Surface heating is slow and also irregular at the surfaces, edges and corners. These areas are hotter than a material's interior. As a result, the quality of conventionally heated materials varies and the desired result are often not met (Kingman, 1999). In microwave drying, the outer surfaces of the molecules are actuated first. The material's interior is heated as the heat flows inward from the outer layers, and most of the moisture is removed from the material by evaporation (Haque, 1999). It is possible to equally heat a volume material with microwave dryers. This is known as volumetric heating. In this process, energy is transferred along the material electromagnetically rather than as a thermal flow of heat. Therefore, the amount of heat transferred is not limited, and the order of heat distribution is considerably increased. Advantages of microwave heating over conventional heating also include a shorter heating time, lower humidity levels, increased production rates, and reduced manufacturing costs (Tranquilla, 1997).

Metals generally have high conductivity, and microwaves reflect from the surface of the metals because they are not transparent. In effect, they do not heat the metals. Materials that are permeable to microwaves are classified as insulators and are used to support the heating of materials in microwave ovens. Materials that perfectly absorb microwave energy are easily heated and classified as dielectrics (Jones, 2004; Rinkevicha *et al.*, 2014). Pure dolomite ore is permeable to microwaves and hardly heated (Rinkevicha *et al.*, 2014). By means of this feature of the ore, it is possible to apply microwave energy inside the sample without deteriorating the structure of the sample or increasing the surface temperature too much.

In this study, the impact of process parameters on the drying of a dolomite ore by microwave energy was investigated. The aim was a maximum moisture content of 0.10% in order to utilize the openly stocked dolomite ore in the glass industry.

2. Materials and methodology

Microwave energy drying tests were carried out on samples taken from an open stock area of a mining company in the vicinity of Izmir, Turkey that produces dolomite ore at a rate of 98% whiteness.

2.1 Characterization of the dolomite ore sample

Chemical analysis of the sample was carried to determine the content and purity of the samples used in the experiments for parameter screening purposes (Table 1). The purity of the dolomite ore sample with $CaCO_3$ and $MgCO_3$ content was found to be 98.1%. Due to the decomposition of carbonates and release of CO_2, the results were stated as the sum of major oxides and a loss on ignition. Based upon the high purity of the dolomite sample used in the experiments, it was expected that the microwave energy would be homogeneously distributed. It was also surmised that impurities would not cause unexpected sudden temperature increases.

Table 1. Chemical analysis results of the dolomite sample used in the experiments

Major Oxides	%
CaO	31.62
MgO	20.64
Fe_2O_3	0.03
SiO_2 +Al_2O_3 + Na_2O + K_2O	0.16
LOI*	47.55

**LOI: Loss on ignition*

2.2 Sample Preparation

The dolomite samples used in the microwave drying experiments were graded to a size of -2 mm by gradual and controlled crushing, which correlates to the ore stockpile. In order to moisturize the samples in the range of 4.5-5% moisture content, 0.5 g of water was added to 10 g of the almost dry dolomite sample with 0.02% of the initial moisture content in the refractory pots. The it was fed into the microwave. The measured moisture values of the samples were 4.71%, while the calculated theoretical moisture was 4.76%. The constant experimental conditions are given in Table 2. The sample preparation method does not change even when working with different initial moisture contents. The only change was the amount of water.

Table 2. Constant experimental conditions in microwave drying tests

Experimental Condition	Value
Max. particle size (mm)	2
Solid sample amount (g)	10
Additional water (g)	0.5
Theoretical moisture (%)	4.76
Moisture measured (%)	4.71

2.3 Equipment used in the Experiments

A home-type, Bosch brand microwave oven with dimensions of 290x46x351 mm, frequency of 50 Hz, 5 stages of (800/600/360/180/90W) power adjustment was used in the experiments. Moisture analysis devices are measurement instruments designed to determine the moisture content of various samples. For this purpose, measurements were conducted using a MAC brand moisture analyzer. The Sparker brand DT-8858 infrared thermometer with a measuring capacity of -50°C to 1300°C was used in order to determine the surface temperatures before and after microwave heating. The mean surface temperatures of the samples were obtained by thermographic imaging using a FLIR brand E50 model thermal camera. The thermal imaging determines the surface temperature of objects by the colors and shapes formed from the heat. In this method, the thermal energy reflected from the surface in the infrared band can be presented as a spectrally visible color spectrum in which each energy level is represented by different colors (Grinzato *et al.*, 1998; Popov *et al.*, 1999; Peterson, 2002; Luong, 2004; Meola *et al.*, 2005; Avdelidis *et al.*, 2007).

Examples of thermographic images used in surface temperature measurements are given in Figure 1. While single point measurements can be observed in the examples, the average area surface temperature data was used in the experiments.

2.4 Methodology of drying tests

The surface temperature and moisture content measurements of the samples prepared in the refractory pots were taken at various stages during drying tests. Different samples were prepared for each test duration and microwave power in order to prevent the natural changes in moisture content with respect to time. The surface temperatures of the samples were measured with the infrared thermometer and thermal camera before and after the experiments. Thermal camera measurements were benefited from in the test results, and infrared thermometer measurements were used for control purposes. Based on these measurements, changes in surface temperatures and moisture contents were calculated.

Fig. 1. Thermographic images and surface temperature measurement examples.

3. Results and discussion

In microwave drying experiments, the initial and final moisture contents, loss in moisture, initial and final surface temperatures, and the temperature difference of the dolomite samples were determined at different microwave oven powers. Time-dependent changes in moisture and surface temperatures were observed at microwave oven powers of 180, 600 and 800W. Table 3 shows the results of the experiments in which the constant initial moisture content was 4.71% and the maximum particle size was -2 mm.

Table 3. Experimental results with regard to microwave power and duration

MW Power (W)	Duration (minutes)	Final Moisture (%)	Loss in Moisture (%)	Initial Surface Temp. (°C)	Final Surface Temp. (°C)	ΔT (°C)
180	2	3.67	22.04	26.2	43.8	17.6
180	4	2.45	48.07	26.2	44.9	18.7
180	6	1.79	62.00	26.3	49.6	23.3
180	8	0.88	81.40	25.3	54.6	29.3
180	10	0.48	89.87	25.9	62.5	36.6
180	12	0.37	92.14	21.1	54.9	33.8
180	14	0.02	99.58	20.2	58.8	38.6
600	2	3.47	26.28	26.6	52.5	25.9
600	4	1.98	57.90	26.3	56.7	30.4
600	6	0.94	80.15	26.0	68.6	42.6
600	8	0.42	91.10	25.9	72.1	46.2
600	10	0.15	96.82	26.5	76.2	49.7
800	2	2.48	47.39	26.0	58.3	32.3
800	4	2.11	55.27	25.5	61.2	35.7
800	6	1.05	77.66	26.5	65.0	38.5
800	8	0.16	96.58	26.5	73.9	47.4
800	10	0.01	99.79	25.2	74.7	49.5

The drying tests were performed at three different microwave powers on dolomite samples with about 5% moisture content in order to determine the time required to accept the samples as dry. The samples were considered dried at 8 minutes for 800W, 10 minutes for 600W and 14 minutes for 180W. The graphical illustrations of loss in moisture, duration and surface temperature changes for tests performed at 180, 600 and 800W microwave oven powers are given in Figures 2, 3 and 4, respectively.

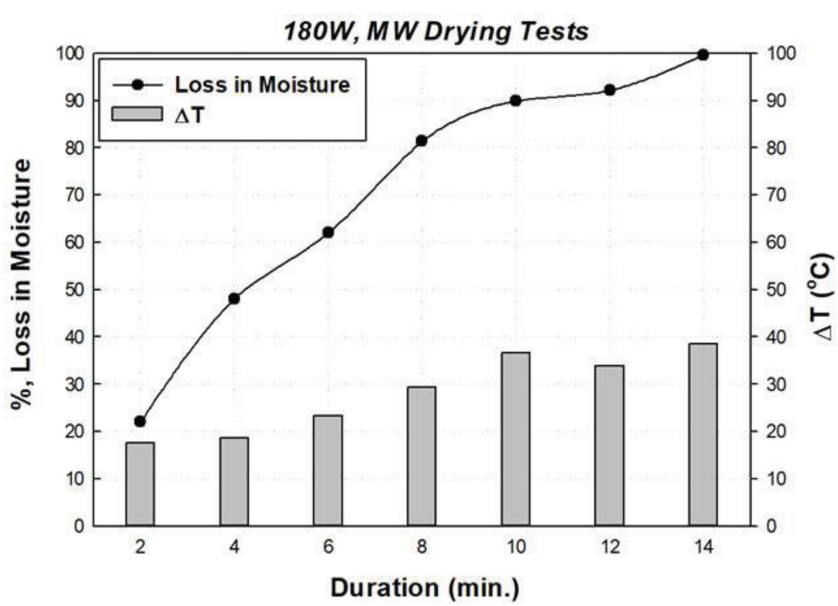

Fig. 2. Loss in moisture and surface temperature changes of samples at 180W MW oven power with respect to duration.

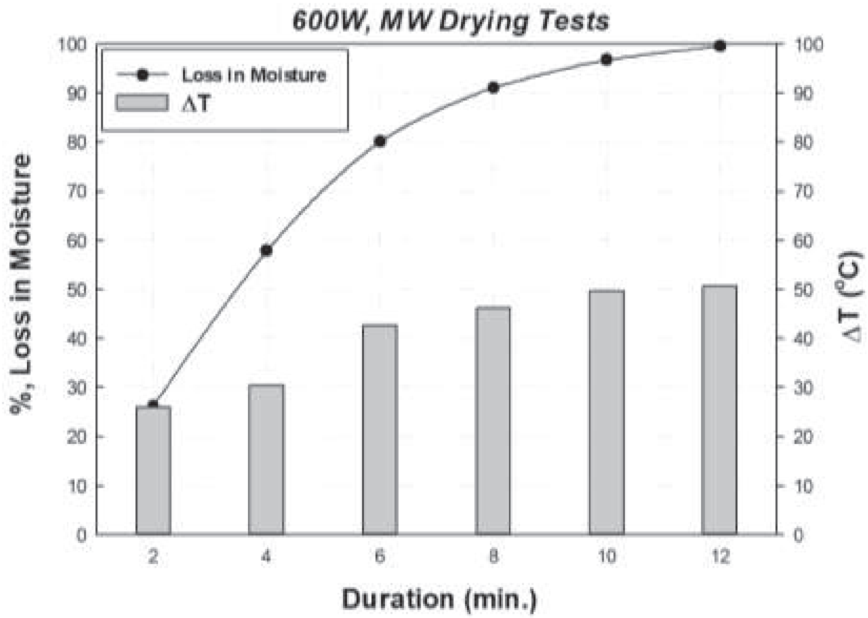

Fig. 3. Loss in moisture and surface temperature changes of samples at 600W MW oven power with respect to duration.

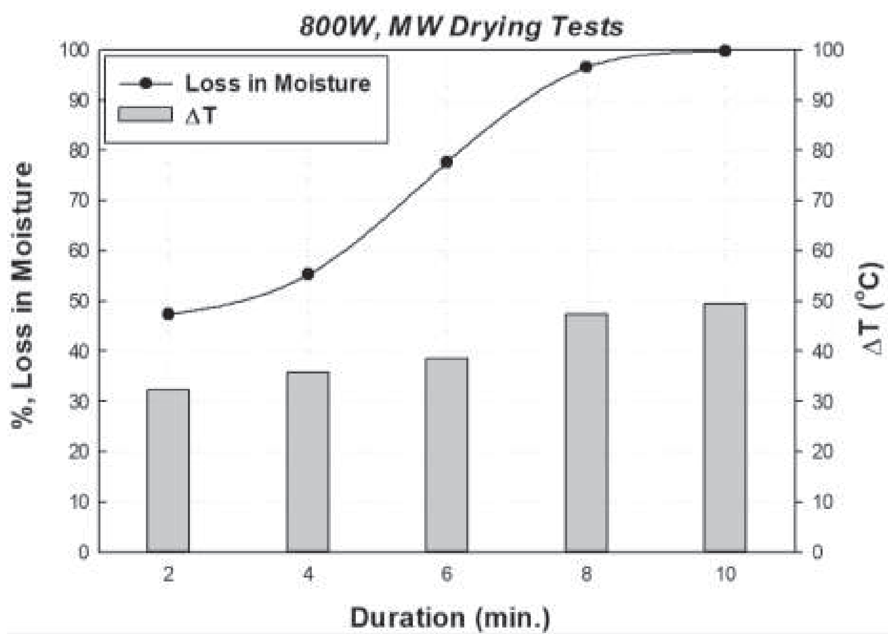

Fig. 4. Loss in moisture and surface temperature changes of samples at 800W MW oven power with respect to duration.

Even at a microwave oven power as low as 180W, it was possible to completely remove the surface moisture from the dolomite samples. On the other hand, at 800W, the dolomite samples were almost dry after 8 minutes. The highest surface temperature encountered in the experiments was approximately 76 °C, which is below the temperature levels reached with conventional furnaces. The application of microwave energy in drying the surface moisture of dolomite ores was successfully performed without a major increase in the surface temperature and without deteriorating the structure of the ore samples.

The impact of the initial moisture content on drying process was determined by changing the initial moisture content to between 4.71% and 33.3% at optimum experimental conditions which were fixed as 800W of microwave oven power and 8 minutes of drying duration. The samples with different initial moisture contents reached the dry level at the given conditions (Fig. 5). The microwave oven that the experiments performed was able to dry the dolomite sample with an initial moisture content of 33.3% after 8 minutes of operation at 800W.

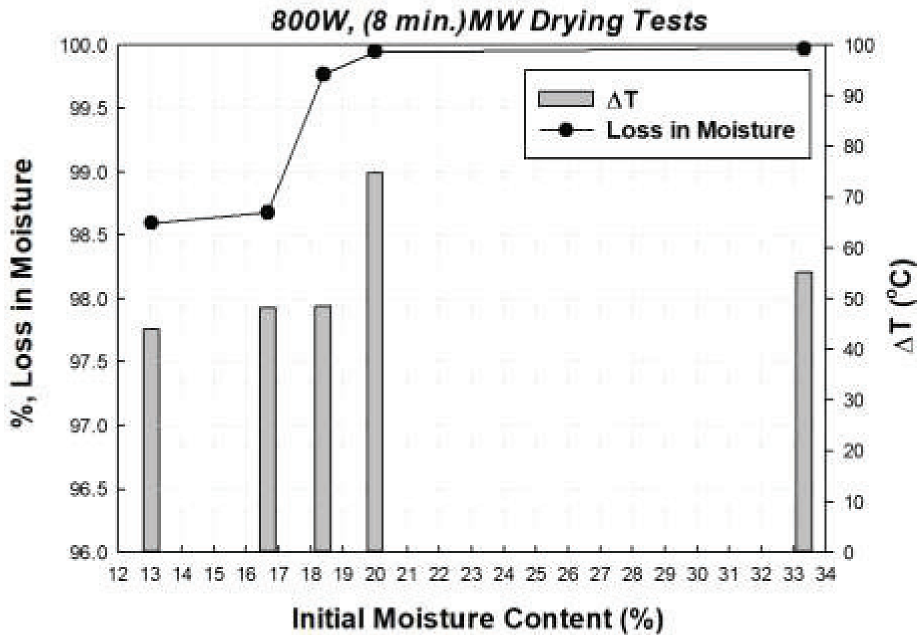

Fig. 5. Rate of moisture loss and surface temperature changes of dolomite samples at different initial moisture contents after 8 minutes.

4. Conclusions

Microwave drying tests performed on dolomite samples show that dolomite is permeable to microwaves, as stated in the literature. Its surface does not heat up as much as other minerals. The temperature differences which occurred on the surface of the mineral were the result of heating the dolomite surface by convection (contact and vibration) by microwave heated water molecules that provided the surface moisture. The high purity of the dolomite samples allowed the microwave energy to spread homogeneously through the mineral and prevented unexpected, sudden temperature increases due to impurities.

Dolomite samples containing about 5% moisture were prepared, and drying tests were performed at three different microwave powers to determine the duration required for the samples to achieve their initial moisture content, which was assumed to be dry.

The application of industrial microwave ovens with very low capacities is a hindrance for activities that require large capacities, such as mining. For this reason, in evaluation of the results, rather than energy consumption, the moisture removal rate and as a consequence, the increase in capacity were taken into consideration.

The initial moisture content was increased by fixing microwave oven power to 800W and drying duration to 8 minutes, the moisture content that could be removed was determined. In the experiments, samples with moisture contents ranging from 5% to 33.3% were completely dried. This demonstrates that the microwave energy would dry out even higher amounts of ore with the determined power and duration. Since all these experiments were carried out with fixed sample amounts, it would be beneficial to repeat the optimization of capacity, power and duration in an industrial scale microwave oven.

This study shows that it is possible to dry dolomite ores with microwave energy. This process is beneficial as compared to conventional oven drying because there is no structural deterioration of the sample and surface temperature do not need to be high. The number of manufacturing companies that produce industrial scale microwave ovens. Therefore, there will be more opportunities to use them for drying ores. The consideration and evaluation of applicability of microwave energy in mineral industries could bring new advancements to drying processes.

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