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Designing Jaw Crusher and Rotary Dryer Equipment for the Production Process of Acid-activated Bentonite

Majid Hayati-Ashtiani¹✉^{ID}, Hadiseh Tavakoli²^{ID}

¹Department of Chemical Engineering, Faculty of Engineering, University of Kashan, Iran. Email: hayati@kashanu.ac.ir

²Department of Chemical Engineering, Faculty of Engineering, University of Kashan, Iran. Email: workshopjoint@gmail.com

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ABSTRACT

Industrial clay Bentonite consists of the nanostructure and nanoporous mineral montmorillonite. The most important applications of bentonite and its modified types include the absorption and release of salicylic acid (aspirin), the use of Layered Nano Clays (LDH) in combination with biological materials, vitamins, drugs, and DNA; the use in wound healing, disinfectant with 95% absorption of the coronavirus, and prevention and treatment of coronavirus. This study aims to design a jaw crusher and a rotary dryer for extracting valuable minerals, and utilizing the MATLAB software tool for modeling and design calculations. In developing the crusher, based on the guidelines of the references and considering the energy consumption of crushing, the average crushing ratio was selected as 3. Regarding the dryer, the inlet air was at ambient (30°C and 1 bar), and the number of theoretical heat transfer units was assumed to be the average value suggested by the sources, i.e., 2. In the jaw crusher design, the crusher opening distance is calculated to be 6.22 inches. By performing the calculations, the most important results of the dryer are that the diameter and length of the rotary dryer are calculated to be 1.06 and 7.77 m, respectively.

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1. Introduction

Bentonite is an industrial clay that consists of the nanostructured and nanoporous mineral montmorillonite (a member of the smectite family). Montmorillonite, as the most important constituent, affects all the properties of bentonite. The following are some of the applications of bentonite and its modified types: absorption of salicylic acid (aspirin)

by bentonite adsorbents and bentonite modified with organic materials [1], fuller's earth for cleansing skin and hair [2], use of layered nanoclays (LDH) in combination with biological materials, vitamins, drugs and DNA [3], use of bentonite in pelotherapy (mud therapy) [4], clay beauty face mask for exfoliating facial skin [5], use of clay in wound healing [6], disinfectant with 95% absorption of coronavirus by bentonite from surfaces [7], use of nanoclays for prevention and treatment of coronavirus [8].

Bentonite has been used in Iran for washing clothes since ancient times. This cleaning agent was known as soap clay. Fuller's earth, which is another name for bentonite, was used for washing the hair. The use of clays as soap has been popular since 2500 B.C., during the time of the Sumerians. Minerals were used in cosmetic and medicinal purposes during the reign of King Hammurabi of Babylon. The use of modified clays in Europe times back to the discovery of a bentonite mine in Bavaria, Germany, in 1900 A.D. Other bentonite mines were discovered between 1906 and 1909 A.D., which were first used in cement and then in adhesives. In 1909 A.D., the Sud Chemie AG Company used bentonites for the industrial production of a type of bleaching earth called Tonsil [9].

Drying bentonites results in better crushing. If mineral rocks are not partially dried, their particles stick together during crushing, and their crushing becomes difficult. Crushing bentonite increases the surface area and, as a result, properties resulting from the increased surface area, such as greater absorption capacity, higher cation exchange capacity, etc. These cases necessitate the design of drying and crushing equipment. Researchers have shown that the way bentonite is crushed has an important effect on water adsorption capacity. The amount of water adsorption is effective in burying toxic materials, where bentonite prevents the leakage of buried materials.

The most commonly used equipment for size reduction are jaw and gyratory crushers [10]. A jaw crusher grinds the Bentonite between a vertical fixed and a moving plate [10]. A gyratory crusher is essentially a giant pestle and mortar in which the solids are ground between a vibrating inner and stationary outer cone. The size of the outlet opening determines the maximum particle dimension that is produced in both types of crusher. If a finer particle size is required, then additional grinding machinery must be used downstream of the crusher. Sometime two crushers will be used in series, with the downstream crusher having a narrower outlet to produce smaller particles. The bentonite particles used in this study were crushed by a jaw crusher, and the particle size distribution was in the range of 0.075 to 15mm [11]. The presence of different gears in the design of jaw crushers causes the size distribution of bentonite particles, which are later distributed in the range of 0.075 to 15mm with the help of different sieves [12-13]. Another factor that affects the water adsorption of bentonites is the drying method. Initial drying of bentonite at 60 °C in processes involving bentonite facilitates the crushing of bentonite and affects the physical properties of bentonite, like the dry density of bentonite. Subsequently, dryers like rotary dryers are usually required to perform supplementary drying at higher temperatures, such as 110°C [14].

The purpose of this research is innovative approach to design equipment for a jaw crusher and a rotary dryer, which are two important types of equipment used in the production of various products within the processes of mineral and chemical industries, including the production process of high quality acid-activated bentonite. Literature reports theoretical advantages for design equipment for a jaw crusher and a rotary dryer, but we used experimental data carried out at an industrial scale design. For this purpose, after studying the production process, the need for a jaw crusher at the beginning of the production process and a rotary dryer in preparing the final product of acid-activated bentonite was identified. Then, considering the assumptions and criteria for the design of the acid-activated bentonite production process, the two aforementioned devices were designed along with programming using MATLAB

software. The novel insight provided in this study is a new approach through which it is possible to model and design a jaw crusher and a rotary dryer using MATLAB software codes.

2. Concepts and methodology

2.1. Process description

Most chemical engineering processes that are designed, developed, and updated have reaction [15] and separation [16] sections. Part of this design, which is considered at the beginning of the design, is the conceptual design of the process. In the meantime, various simulation software such as the Aspen family of software from Aspen Tech Company can be used [17]. In the following, the design of the production process of acid-activated bentonite in different stages is discussed.

A brief and simplified diagram of the production process of acid-activated bentonite is shown in Fig. 1. The production process of acid-activated bentonite can be summarized in 9 stages, along with the required devices in each section. 1- Crushing and granulation stage including hopper with scale, vibrating feeder, crusher, vibrating screen, elevator, silo, conveyor belt, magnet for separating chips and iron particles, 2- Mixing and separation stage for impurities such as free silica (quartz) including mixing tank(s), pump, sieve feed splitter, hydrocyclone or tank, backhoe tractor for transporting free silica impurities, 3- Clay modification stage using modification solution including modification reactor(s), resistant pump(s) to modification solution, storage tank(s), 4- Washing and thickening stage including washing thickener(s), discharge pump(s) of thickener effluent, storage silo(s), modified clay transfer pump(s) resistant to the modification solution, 5- Dewatering and packaging stage including Feeder filter(s), dryer(s), silo(s); and product packaging station, 6- The modification solution stage includes a concentrated modification solution storage tank, preferably stainless steel with a rubber inner lining, a concentrated reforming solution transfer pump, a reforming solution dilution tank, and a diluted modification solution transfer pump(s), 7- The utilities stage (water, electricity, gas, and steam) includes a boiler, heat exchanger, and electric motor, 8- The waste-water stage includes sedimentation pond(s), pump(s) resistant to low pH of the modification solution, water, and wastewater treatment system, 9- The effluent neutralization section stage (if needed) includes a neutralization solution preparation tank, such as caustic soda, a pump for sending the neutralizing solution, a wastewater neutralization reactor, and a wastewater discharge pump.

As can be seen from the description of the above process, the two most important devices in this process, the jaw crusher and the rotary dryer, are the ones whose equipment design is discussed in this research. Reactions 1 and 2 show that the reaction mechanism of bentonite acid activation is first-order [18]:



From a thermodynamic point of view, by acid-activation of bentonite, the cations in the bentonite structure are exchanged with hydrogen ions of the acid. This exchange is due to the thermodynamic force that exists between the cations and hydrogen ions. The hydrogen ions of the acid, due to their positive charge, have a greater tendency to form bonds with the bentonite structure and therefore replace the calcium ions. This exchange of cations causes the structure of bentonite to change. As a result, delamination of the bentonite layers occurs, and its porosity and active surface area increase.

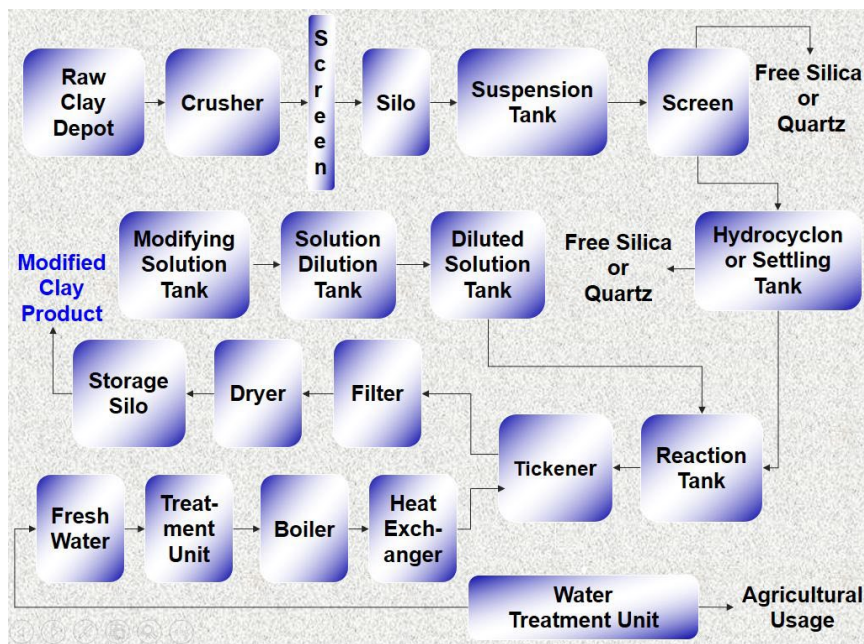


Fig. 1. Block flow diagram of the production process of acid-activated

This process is also accompanied by an increase in the system entropy. Entropy is a measure of the amount of disorder in a system. In this process, the amount of disorder in the system increases as hydrogen ions enter the bentonite structure and the layers exfoliate.

2.2. Jaw crusher

The first stage in the crushing process, the main purpose of which is to release valuable minerals, is called crushing. The crushing operation is dry and is carried out in 2 or 3 stages.

The stones first are crushed to a size of 10 to 20 cm in primary crushers such as jaw crushers. The distinguishing feature of this type of crusher is the two plates that can be opened and closed. The jaws are arranged at an angle to each other. In this type of crusher, there is one fixed jaw and one movable jaw. Fig. 2 shows a type of jaw crusher [19].

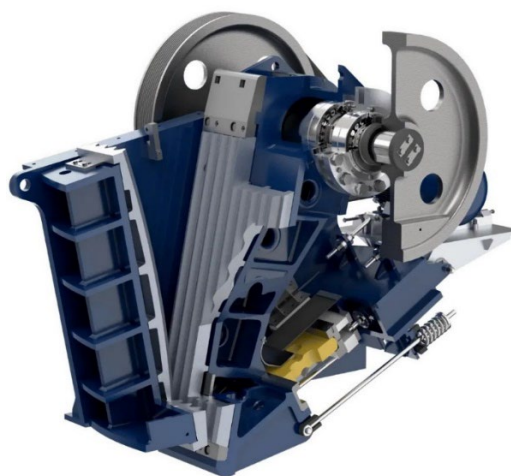


Fig. 2. Jaw crusher [19]

Jaw crushers are used in small and medium-sized mines for primary crushing of materials, crushing of low hardness materials such as bentonite. Jaw crushers consume a lot of energy to crush rocks, which is supplied from two sources: electrical energy for the machine's motor and mechanical energy to transmit motion to the jaws. The amount of energy

consumed depends on the motor power, the electrical and mechanical efficiency of the machine, and the type and size of the input rocks. The motor of a jaw crusher must have sufficient power to transmit mechanical power to the jaws. The motor power depends on various factors such as the size of the crusher, the type of rock, and the output capacity. Usually, motors with a power of 50 to 150 hp are used for medium-capacity jaw crushers [20].

Jaw crushers and gyratory crushers are both crushing equipment used in various industries, but they have major differences in performance and application. Jaw crushers crush materials using two fixed and movable jaws, while gyratory crushers crush materials by rotating a plate and applying pressure to the rock.

Other key differences between jaw crushers and gyratory crushers are in the type of movement, crushing capacity, output uniformity, and cost. In terms of movement, jaw crushers crush materials by moving the jaws against each other, and gyratory crushers crush materials by rotating the plates. In terms of crushing capacity, gyratory crushers typically have higher crushing capacities and are suitable for crushing larger volumes of material, while jaw crushers are suitable for medium crushing. In terms of output uniformity, gyratory crushers produce a more uniform crushed product and are more suitable for applications that require uniform particle size. Finally, jaw crushers typically have lower initial costs and are easier to maintain.

2.3. Rotary dryer

A rotary dryer consists of a cylindrical shell rotating horizontally and slightly inclined towards the feed outlet (Fig. 3). The wet material enters the cylinder at one end, and the dried product exits at the other. As the cylinder rotates, the lifting vanes lift the solids and throw them into the flowing hot air, resulting in the solids being completely exposed to the hot air, effectively drying the material.

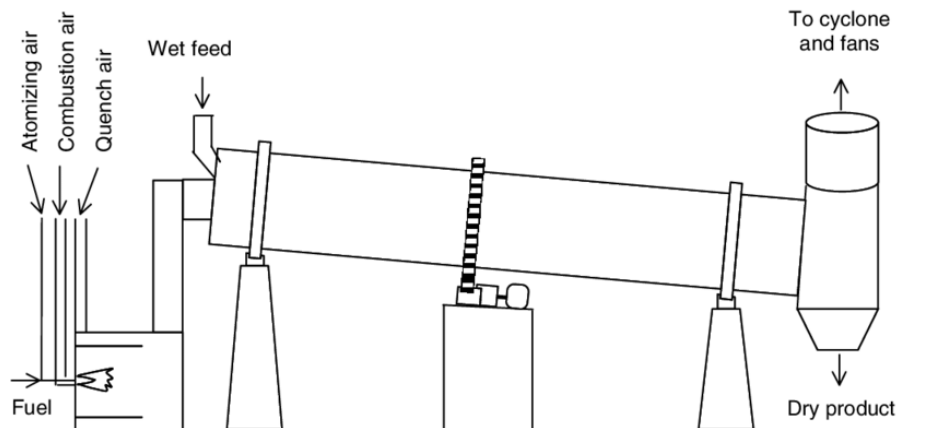


Fig. 3. Rotary dryer [19]

There are several sensitive variables whose sensitivity should be considered in the design of rotary dryers to optimize the performance and efficiency of the equipment. These variables include the length and diameter of the equipment, the inclination of the equipment, the speed of rotation, the type and amount of air flow, as well as the type and amount of input material. The length and diameter of the equipment are the most important design variables in rotary dryers, which are emphasized in this research. These variables affect the amount of input material and drying time. Longer equipment with a larger diameter can usually dry a larger amount of material in a given period [21-22].

Drying in a rotary dryer is, in turn, a very complex process because, in addition to thermal drying, it also involves the movement of particles within the dryer, which requires consideration of all the critical design variables mentioned.

2.3.1. Heat transfer coefficient models

The prediction of the volumetric heat transfer coefficient using a relationship is important for designing rotary dryers. The volumetric heat transfer coefficient means the amount of heat transferred from a unit volume of the cylinder under the effect of the driving force of the temperature difference. The rate of heat transfer between hot air and solids is expressed by Eq. (3):

$$Q = U_V V_V \Delta T_{lm} \quad (3)$$

where Q is the rate of heat transfer between air and solid materials in W, U_V is the volumetric heat transfer coefficient in $W/m^3.K$, V_v is the volume of the cylinder in m^3 , ΔT_{lm} is the logarithmic temperature difference between the temperature of hot air and solids at the inlet and outlet of the dryer in terms of K [23]. Much research has been done on obtaining an equation to predict the volumetric heat transfer coefficient. Most of the work done in this field can be expressed by Eq. (4):

$$U_V = \frac{k}{D} G^n \quad (4)$$

In Eq. (4), U_V is the volumetric heat transfer coefficient, G is the air mass flux, D is the cylinder inner diameter, k and n are empirical constants whose values depend on the solid characteristics, the geometry of the lifting vanes, the cylinder rotation speed, and the amount of mass remaining in the dryer. It is possible to determine the values of these constants from experimental data using a small-scale dryer [24-25].

2.4. Equipment design assumptions and criteria

The crushing ratio indicates the amount of material size reduction. The higher this ratio means the more crushing, but it requires more energy. This ratio is usually suggested to be 6:1, and in this design, the average value of 3:1 was chosen [20]. Finally, assuming that particles smaller than 66.66 mm are equal to 20%, a square sieve with an opening of 66.66 mm is placed. In the design of the jaw crusher, it is assumed that the access time of 70% of the particles is the useful time of the entire production.

The assumed conditions of the air entering the dryer are 30°C, 1 bar pressure, 5000kg/hr- m^2 velocity, and 93% relative humidity. In calculating the overall heat transfer coefficient of the dryer, the constant coefficients k and n are considered to be 4.75 and 0.67, respectively. N_r is the number of heat transfer units based on gas and in rotary dryers; when its value is between 1.5 and 2.5, the dryer has the most economical performance. In this design, this average value is assumed to be 2. In the dryer design, the inlet air flow rate is constant, and in the more advanced case, the inlet air flow rate is variable, and all calculations are repeated.

In the design of the dryer, the specific weight of bentonite is 1.8g/cm³, and the bentonite feed entering the crusher is 200mm with an 80% passing size. The bentonite process capacity is assumed to be 35tons/day, operating at an interval of 8h.

3. Results and discussion

3.1. Jaw crusher design

Factors affecting the size and type of crusher include: 1- Plant capacity or ore delivery schedule, 2- Feed size, 3- Desired product size in downstream processing, 4- Ore characteristics including rock hardness, clay and sand content, and input fluctuations, 5- Weather conditions, 6- Downstream processes. Factors affecting the design of the crushing

process include: 1- crushing capability, 2- Maximum dimensions of rocks being crushed, 3- Required product dimensions, 4- Abrasion rate, 5- Capacity.

For crushing bentonite, the work index is 16.5kWh/ton. The product must be smaller than 50mm. Assuming 75% access time, the useful working time of the factory is equal to:

$$0.75 \times 8 = 6 \text{ h} \quad (5)$$

Considering that the daily process input requirement is 35tons/day, the minimum capacity of this plant is equal to:

$$T = \frac{35}{6} = 5.83 \frac{\text{ton}}{\text{h}} \quad (6)$$

The density of bentonite varies greatly depending on its quality and may vary from 2.2 to 2.8g/cm³. Its apparent density, when it loses its moisture under natural conditions, is between 1.5 and 1.8g/cm³. Considering that under natural conditions, the specific gravity of bentonite is 1.8g/cm³. As a result, the volume of processing per hour:

$$\frac{5.83}{1.8} = 3.24 \frac{\text{m}^3}{\text{h}} \quad (7)$$

Assuming that the bentonite feed entering the crusher is 200mm with an 80% passing size. By choosing a crushing ratio of 3 according to the energy requirement, the throat size of this jaw crusher will be equal to [20]:

$$\frac{200}{3} = 66.66 \text{ mm} \quad (8)$$

Assuming that particles smaller than 66.66 mm are 20%, by placing a square screen with an opening of 66.66 mm in the path of the incoming particles, the capacity of this crusher can be calculated according to Eq. (9):

$$33.33 \times 0.8 = 26.66 \quad (9)$$

On the other hand, since the specific gravity of 1.6g/cm³ is considered for the crushing curves, as a result:

$$26.66 \times 1.6 = 42.66 \quad (10)$$

According to the calculations, from jaw crushers and referring to references [20], a 500×800 crusher with a capacity between 45 and 60ton/h and a power consumption between 65 and 75kW with a 67mm throat will be suitable. By choosing a jaw crusher, the process needs are met and additional costs are avoided. Using the Bond Equation, the required power can be calculated from Eqs. (11) and (12):

$$W = \frac{11 \times 16.5}{\sqrt{67000}} - \frac{11 \times 16.5}{\sqrt{200000}} = 0.30 \frac{\text{kWh}}{\text{t}} \quad (11)$$

$$\text{Power (kW)} = 0.30 \left(\frac{\text{kWh}}{\text{t}} \right) \times 33.33 \times 1.8 \left(\frac{\text{t}}{\text{h}} \right) \times 2 = 36.80 \text{ kW} \quad (12)$$

Considering the capacity of the plant, using the Taggart Equation used to select the appropriate crusher, the jaw crusher opening distance is obtained from Eq. (13).

$$\frac{6}{D^2} < 0.16 \Rightarrow \frac{6}{D^2} - 0.16 < 0 \Rightarrow D > 6.22 \quad (13)$$

3.2. Rotary dryer design

Regarding the production process of acid-activated bentonite, the length of the rotary dryer and the diameter are studied in order to design and analyze part of it.

3.2.1. Calculation of dryer diameter

The bentonite processing capacity is 35 tons/h. If the working period of this process is 8 h, the bentonite entering the dryer will be 4375 kg/h, and the amount of air entering the dryer under ambient conditions (temperature 30°C and pressure 1bar) is between 2000-25000kg/h.m² [21], which in this problem is assumed to be 5000kg/h.m². The cross-sectional area of the dryer can be calculated from Eq. (14):

$$A = \frac{m_a}{G} = \frac{4375}{5000} = 0.88 \text{ m}^2 \quad (14)$$

Where A is the cross-sectional area of the dryer (m²), m_a is the inlet flow rate (kg/hr), and G is the air mass flux (kg/h.m²). Given the circular cross-sectional area, the diameter of the dryer is calculated from Eq. (15):

$$D = \sqrt{\frac{4 \times A}{\pi}} = \sqrt{\frac{4 \times 0.88}{\pi}} = 1.06 \text{ m} \quad (15)$$

The diameter of the dryer varies from 1 to 3m [21]. Therefore, the calculated drying diameter is accepted. Now, considering the variability of the inlet air velocity from 2000 to 25000kg/h.m² and considering this range, the diameter values for the dryer have been coded within MATLAB, and the effect of varying the design inlet air mass flux on the dryer diameter (sensitivity analysis) has been investigated. Fig. 4 shows the optimum case for the diameter of the rotary dryer.

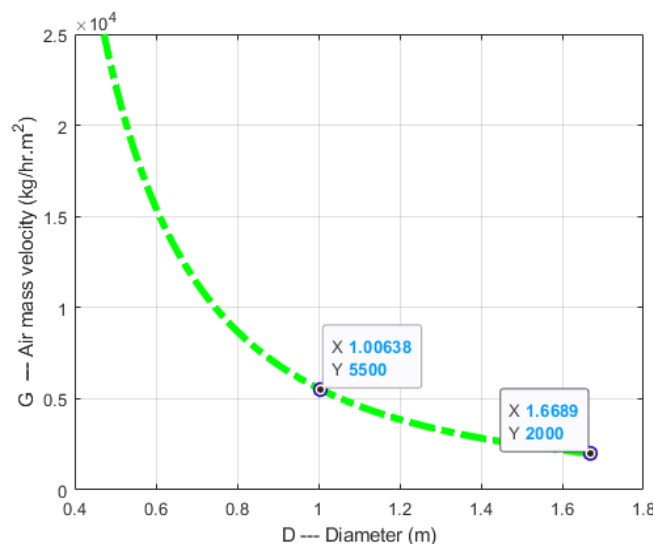


Fig. 4. Diagram of dryer diameter versus air mass velocity

As mentioned, the diameter of the dryer varies from 1 to 3m. According to Fig. 4, the maximum air mass flux is observed at the optimal diameter of 1 m, which was designed in this study to achieve this number. This maximum mass flux causes faster drying of the materials, better heat transfer, and increased dryer efficiency. The type of bentonite (which was carried out by conducting special instrumental and laboratory tests to determine the characteristics of the dryer by the authors of the study) and its moisture content are influential in the design of the rotary dryer. The amount of heat required for drying bentonite is calculated using Eq. (16).

$$Q_t = m C_p \Delta T \quad (16)$$

where Q_t is the amount of heat required to dry bentonite (kJ or kCal), m is the mass of bentonite being dried (kg), C_p is the heat capacity (J/kg.K) and, ΔT is the temperature difference (°C) before and after drying. Using an ambient temperature of 30°C and a relative humidity of %RH=93 from hygrometer charts (such as Perry's Handbook), humidity (H) = 0.03kg water per kg dry air, gives the specific heat capacity of moist air (C_s) based on Eq. (17) [22]:

$$C_s = 1.005 + 1.88 H = 1.005 + 1.88 (0.03) \quad (17)$$

$$C_s = 1.05 \frac{\text{kJ}}{\text{kg.K}} \quad (18)$$

Now, the heat rate for the dryer is calculated from Eq. (18) (based on 1 hour):

$$Q = 299276.25 \frac{\text{kJ}}{\text{hr}} \quad (19)$$

Empirical Eq. (20) is used to calculate the overall heat transfer coefficient from the Perry Handbook with index $n=0.67$ [22]. As suggested by AIChE for SI units, the value of k is in the range of $3.75 \leq k \leq 5.25$ [26]. Assuming $k = 4.75$, the heat transfer coefficient U_a is:

$$U_a = \frac{kG^n}{D} = 1353.77 \quad (20)$$

To calculate the wet bubble temperature, the most economical operation of the rotary dryer is when N_t (the number of theoretical units of heat transfer) is between 1.5 and 2.5 [21]. If N_t is assumed to be equal to the average value of 2, then the wet bulb temperature (T_w) can be calculated as:

$$N_t = \ln \left(\frac{T_{A_{in}} - T_w}{T_{A_{out}} - T_w} \right) \Rightarrow T_w = 367.98 \text{ } ^\circ\text{C} \quad (21)$$

Given that the inlet air temperature (T_A) is 170°C (443.15K) and the outlet air temperature is 105°C (378.15K), the logarithmic mean temperature difference (ΔT_{lm}) is calculated from Eq. (22):

$$\Delta T_{lm} = \frac{(T_{A_{in}} - T_w) - (T_{A_{out}} - T_w)}{\ln \left(\frac{T_{A_{in}} - T_w}{T_{A_{out}} - T_w} \right)} \Rightarrow \Delta T_{lm} = 32.50 \text{ } ^\circ\text{C} \quad (22)$$

Eq. (24) is used to calculate the length of the dryer:

$$Q = U_a AL(\Delta T)_{lm} \Rightarrow L = \frac{Q}{U_a A(\Delta T)_{lm}} = 7.77 \text{ m} \quad (23)$$

Calculation of the length-to-diameter ratio of the dryer L/D :

$$\frac{L}{D} = 7.37 \quad (24)$$

The L/D ratio for industrial dryers is more efficient between 4 and 10 [23]. Therefore, a length to diameter ratio of 29 can be accepted. Therefore, L and D of the dryer are recommended to be 1.06m and 7.77m, respectively. It is possible to check the variable effect of design inlet air mass flux on L/D dryer length-to-diameter ratio (sensitivity analysis). The L/D ratio is plotted against different air velocity inputs from 2000 to 25000kg/h.m². Fig. 5 is the output of the calculations performed in MATLAB.

Fig. 5 shows that the mass flow of the incoming air to the dryer will increase if the L/D ratio of rotary dryers increases. In this case, the drying efficiency of the equipment will increase, but of course, increasing the length of the dryer will increase the price of the equipment. Finally, according to Fig. 6, the three-dimensional diagram of the length (L), diameter of the dryer (D), and air flow rate entering the dryer (G) has been drawn in MATLAB software. Fig. 6 shows that at a constant dryer length, the mass flow rate of air increases with increasing diameter, which increases drying efficiency. Similarly, at a constant diameter, increasing the length of the dryer will increase drying efficiency because it increases the residence time and contact time of the material being dried. The efficiency of the dryer will be even greater if the flow rate of the hot air stream is also increased under these conditions.

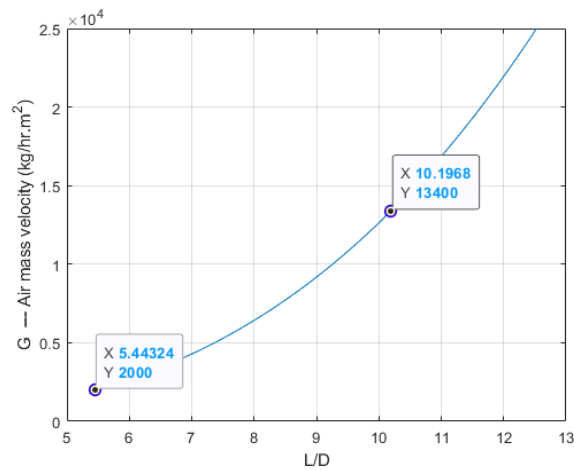


Fig. 5. L/D ratio diagram at different air velocity inlets

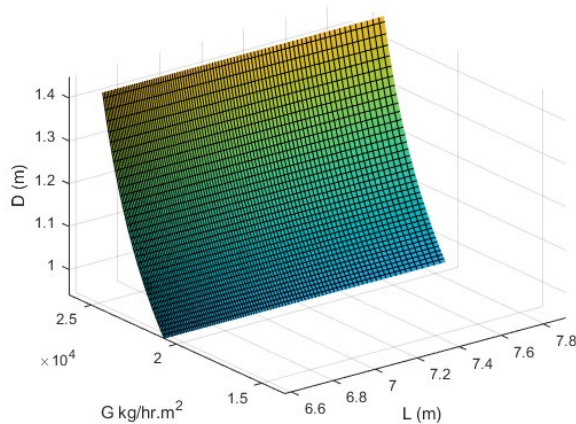


Fig. 6. 3D diagram of dryer inlet length, diameter and air flow rate

4. Conclusion

Jaw crusher has key differences in the type of movement, crushing capacity, output uniformity, and cost compared to other crushers. In this study, the jaw crusher was selected to have a lower initial cost and simple maintenance based on the design conditions. The power required for this crusher was calculated to be 0.3kWh/t in the design of the jaw crusher, and the jaw crusher opening distance was obtained to be 6.22in, which is in line with the standards for crusher construction and fully covers the daily production capacity. Suppose the development of the existing acid-activated bentonite production is required, for example, to increase daily production capacity. In that case, the current equipment will not be suitable, and accordingly, more equipment is considered. The number of reactors is increased, and the process and final equipment are redesigned.

The type of bentonite used, how it is modified, and its moisture content are influential in the design of the crusher and rotary dryer. The type and amount of hot air flow also had to be carefully selected so that the materials were dried uniformly. The air flow should be able to completely remove the moisture from the materials without damaging the materials or reducing the efficiency of the equipment. Three factors of diameter, length, and mass velocity of the incoming air were simultaneously examined in the rotary dryer design. The results showed the diameter of 1.06 m, a length of 7.77 m, and an optimum mass velocity of air between 20,000 and 21,000 for the rotary dryer. In the continuation of the research, it is proposed to examine other types of crusher and dryer equipment and the effect of each model according to the plant capacity, and compare the best equipment model according to their simulation. Dynamic simulation of dryers and crushers in COMSOL Multiphysics and ANSYS software can provide more accurate results for comparing the best equipment model.

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