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Improved Salt Quality and Reduced Energy Consumption via Hot Air Drying

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Abstract. This study examines the effects of hot air drying operating parameters on salt quality and energy consumption. Temperature, air velocity, and drying time were modified to evaluate their effects on NaCl percentage, water content, whiteness, and hot air drying energy consumption. The results showed that increasing temperatures, air velocities, and drying times decreased water content and increased salt temperatures. Additionally, given several operating parameters, NaCl percentage and whiteness initially increased to an optimum value and decreased, respectively. The decrease in NaCl percentage and whiteness is due to salt's rapid decomposition with high-temperature heating to form a yellow residue. Increasing temperatures and drying times increased energy consumption and decreased drying energy efficiency. However, increasing air velocities increased both energy consumption and drying energy efficiency. The most economical values for energy consumption and drying energy efficiency for one operation cycle were 1.79 kWh and 17%, respectively. This study found that the lowest energy consumption and highest energy efficiency while maintaining high salt quality were achieved at 70ºC with an air velocity of 22.5 m/s and a drying time of 30 min.

Keywords: Hot air drying; Hot air performance; Salt; Salt drying; Sodium chloride quality

1. Introduction

Salt is an essential material worldwide, used in many modern industrial applications (Khormali et al., 2016; Aslfattahi et al., 2019; Sofyan et al., 2019), as well as human consumption (Rochwulaningsih et al., 2019a; Rochwulaningsih et al., 2019b). Indonesia's demand for salt has continually grown at a tremendous rate over the last few decades (Juwono, 2020). The country's growing chemical industry and population have accelerated this growth. Consequently, demand has increased for high-quality salt with low production costs. High-quality salt requires that salt be dried to a feasible water content after processing (Zhao et al., 2008). The drying process comprises two phases: heating and drying. It occurs through changes to temperature, relative humidity, and airflow (Palamba

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et al., 2018). The drying process removes water from solid salt particles via evaporation. Drying helps store salt for lengthy periods and improves its quality. The challenge in drying salt is reducing the water content without sacrificing quality since natural elemental impurities—such as sulfate (SO_4^{-2}), calcium (Ca), and magnesium (Mg)—may adversely affect public health (Heydarieh et al., 2020). Moreover, salt drying consumes energy, so its operating parameters must be chosen correctly. For example, a high temperature during salt drying should be avoided because it turns salt yellow (McGee and Diosady, 2016). A variety of strategies are required to obtain the maximum use of positive energy flow production (Harahap et al., 2020). Various drying systems have been applied to salt drying, such as rotary dryers (Jafari and Farahbod, 2017), fluidized bed dryers (Zhao et al., 2008), and hot air dryers (Qadir et al., 2005). Hot air drying has attracted much attention because it offers a wide range of applications, such as drying herbs (Liang et al., 2020), agricultural products (Das and Arora, 2018; Deepika and Sutar, 2018; Gao et al., 2019), and wood products (Khamtree et al., 2019). Operating parameters—such as temperature, air velocity, and drying time—influence product quality when drying with hot air (Zhu, 2018). The current study aimed to investigate the effect of hot air drying parameters—such as temperature, air velocity, and drying time—on salt quality in terms of NaCl percentage, whiteness, and water content. The energy consumption and energy efficiency of hot air drying were also investigated.

2. Materials and Methods

2.1. Salt

Crude solar sea salt with an initial water content of around 11.5% on a wet basis (wb) was used in this study. The salt was obtained from a solar pond in Tajungan Village, Bangkalan Regency, East Java Province, Indonesia. The salt was randomly collected and transported to the experimental site in an aluminum foil pack to minimize environmental effects, such as air humidity and dust, which could have added more impurities to the salt. The undried salt's characteristics are listed in Table 1.

Table 1 Undried salt's characteristics

Salt characteristics	Unit	Information
Source	-	Crude solar sea salt
Actual density	kg/m^3	2,176
Particle size	mm	5–100 mm
Initial NaCl	%	90.7% ± 0.5
Initial whiteness	-	72.5 ± 0.15
Initial water content (wb)	%	11.5%

2.2. Drying Equipment

Hot air heating equipment developed at the salt laboratory at the University of Trunojoyo Madura was used to conduct this study's experiments. A schematic diagram of this hot air heating equipment is presented in Figure 1. The hot air heating equipment was able to control the desired drying conditions over a wide range of operating parameters. Its dimensions were 600 × 400 × 200 mm, and it had a 50-mm thick wire mesh bed and a capacity for 5 kg of crude solar sea salt. The airflow was supplied by a centrifugal blower, which was powered by a 130-watt electric motor. The heater element had a 5-kW capacity and could reach 300°C. The hot air heating motor operated with three phases, AC of 380 volts, and 60 Hz. Air velocity and temperature sensor instrumentation measured the airflow before it entered the dryer box.

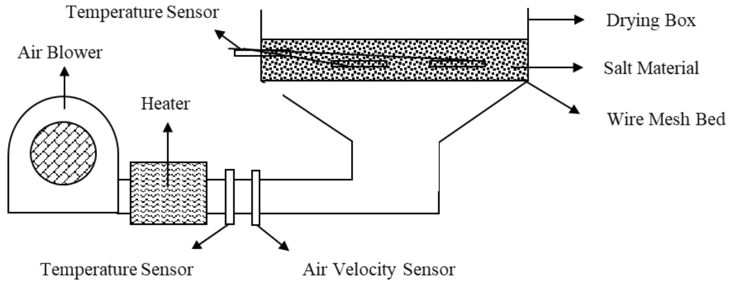

Figure 1 Schematic diagram of the hot air heating equipment

2.3. Experimentation

The crude solar sea salt used as a batch material had a loading weight of 5 kg and an initial water content of 11.5% wb. The study's experiments were conducted at different drying temperatures (50°C, 60°C, 70°C, 80°C, and 90°C), air velocities (17.7, 20, 22.5, 24.4, and 27.5 m/s), and drying times (30, 45, 60, 75, and 90 min.). A flow control instrument regulated the air velocity in the air blower equipment while thermostats in the heater equipment controlled the temperature. The crude solar sea salt was carefully weighed with an electronic digital scale before it was fed into the drying box. The blower and heater were turned on, and once the desired temperature and air velocity were reached, the crude solar sea salt was fed into the drying box. The experiments were conducted by varying the temperature, air velocity, and drying time parameters. During the investigations, one parameter was varied at a time while the other parameters were maintained at a constant value. Every 10 min., the material was mixed with a stainless-steel fork to maintain equal heating. After the drying experiments had been completed, the crude solar sea salt was carefully removed from the drying box and wrapped in aluminum foil to avoid any environmental effects and then packed and sealed into polypropylene bags.

2.4. Water Content

Water content was calculated by measuring losses in mass, determined by drying at 105°C for six hours according to Equation 1:

$$\boldsymbol{Water\ content}\ (\%\ \boldsymbol{wb}) = \frac{\boldsymbol{Initial\ mass}\ (\boldsymbol{g}) - \boldsymbol{Final\ mass}\ (\boldsymbol{g})}{\boldsymbol{Initial\ Mass}\ (\boldsymbol{g})}\ \boldsymbol{x\ 100}\ \% \quad (1)$$

This method followed ISO 2483:1973, a standard for determining mass losses in sodium chloride for industrial use. This international standard specifies a method for determining mass losses at 110°C (conventional moisture) in sodium chloride for industrial use.

2.5. Sodium Chloride Content and Whiteness

The crude solar sea salt's NaCl percentage and whiteness were measured using commercial equipment (Saltdec M102, Matra, Indonesia). This instrument was calibrated with a multifunction calibrator (ADT221A, Additel, USA) with an accuracy of 99.5% ± 0.4.

2.6. Energy Consumption and Drying Energy Efficiency

The drying equipment and blower consumed energy. The electric current was calculated from the power consumed by both the heating equipment and the blower in amps (A), as indicated by a digital electric measuring instrument. The drying equipment's energy consumption was calculated according to Equation 2:

$$E_{electrical} = V \, x \, A \, x \, t_{dry} \tag{2}$$

where V is the electrical voltage (volt), A is the electrical current (ampere), and t_{dry} is the drying time (hr). The amount of heat energy used to remove the water content from the product, divided by the amount of energy consumed by the hot air heating equipment, was calculated as the *drying energy efficiency*. Drying energy efficiency is an excellent way to measure the quality of a drying process. Equation 3 was used to determine drying energy efficiency:

$$\eta = \frac{m_{ew} \gamma_{ew}}{E_{electrical}} \tag{3}$$

where η is the drying energy efficiency, m_{ew} is the mass of removed water (kg), and γ_{ew} is the latent heat of the water's vaporization (kJ/kg).

3. Results and Discussion

3.1. Effect of Drying Temperature

Drying temperatures' effect on drying crude solar sea salt was determined at 50°C, 60°C, 70°C, 80°C, and 90°C, as shown in Figure 2 and Figure 3. During the experiment, the air blower velocity and drying time were kept constant at 27 m/s and 30 min., respectively. As Figure 2 shows, the hot air drying equipment rapidly removed the water content with increasing drying temperatures. The increase in drying temperatures significantly correlated with a rise in salt temperatures.

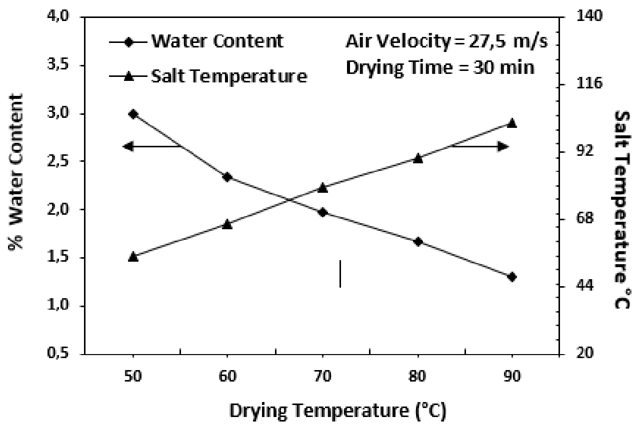

Figure 2 Drying temperatures' effect on salt's water content and temperature

An increase in drying temperature was shown to lead to increased heat supplied to the salt particles, causing rapid water removal. Salt particles have a high heat capacity, which increases their temperature. Drying temperatures' effect on NaCl percentages and whiteness was plotted and shown in Figure 3. When drying temperatures increased, the NaCl percentage and whiteness increased to optimum levels at 80°C and 70°C, respectively. The salt particles' whiteness increased as their surface water content decreased. This whiteness then decreased when the drying temperatures were further increased to 90°C because an increasing NaCl percentage compensated for the water's removal. However, salt easily decomposes with high-temperature heating and forms a yellow residue, which decreases its NaCl percentage and whiteness, as Figure 3 shows.

Heating an alkali halide crystal is known to cause a colored center in the presence of metal or halogen vapor due to a defect in the crystal's lattice (Sonnenfeld, 1995; Li et al., 2010; Kuganathan and Chroneos, 2018; Perera et al., 2019;).

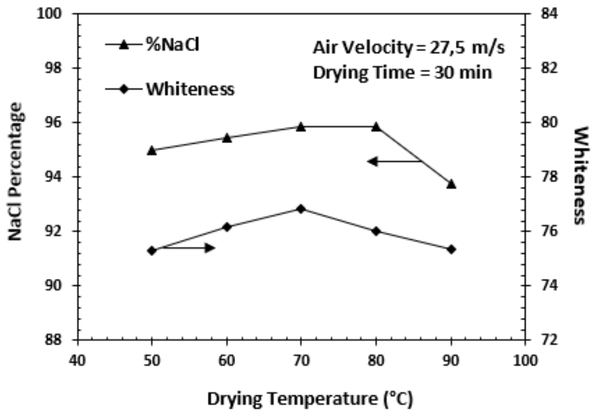

Figure 3 Drying temperatures' effect on NaCl percentage and whiteness

In this work, NaCl crystals were heated in the presence of the metal Na. The NaCl crystals were heated with this Na metal vapor, causing adsorption of Na atoms at the crystals' surface. Sonnenfeld (1995) has long since demonstrated this yellow color in NaCl rock salt.

3.2. Effect of Air Velocity

Air velocities' effect on drying crude solar sea salt was tested at various air velocities (17.7, 20, 22.5, 24.4, and 27.5 m/s), as Figure 4 and Figure 5 show. The drying temperature and drying time were fixed at 70^{o}C and 30 min., respectively.

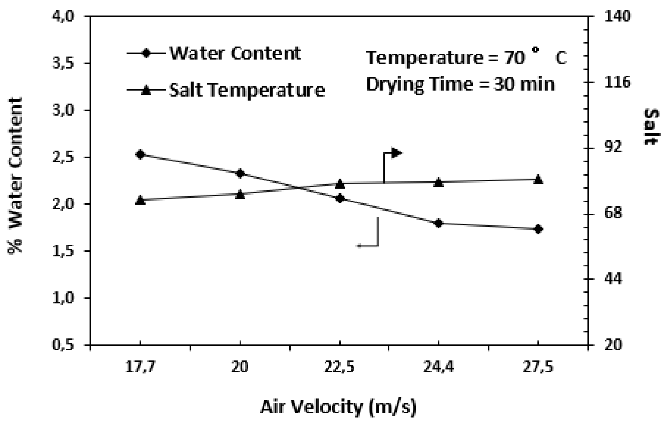

Figure 4 Air velocities' effect on salt's water content and temperature

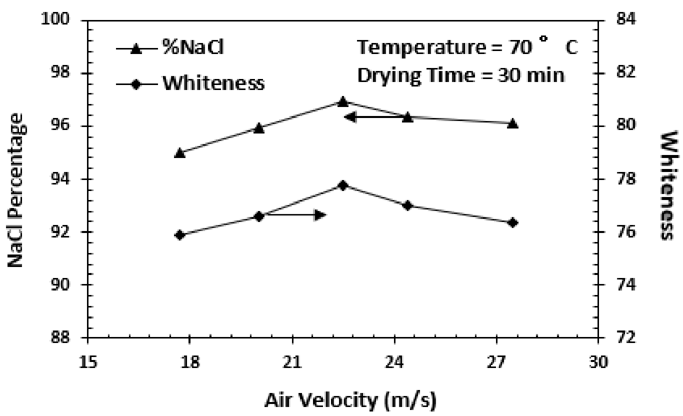

Figure 5 Air velocities' effect on NaCl percentage and whiteness

The water content reduced from 2.53% to 1.73% when the air velocity was increased from 17.7 to 27.5 m/s. Increasing air velocities carried more heat via the airflow, leading to a higher heat transfer from the salt particles and water removal. Furthermore, increasing the air velocity increased the salt particles' temperature from 73.2°C to 80.4°C. The salt's NaCl percentage initially increased to 96.91% as the air velocity increased to 22.5 m/s. Then, it decreased to 96.1% as the air velocity increased up to 27.5 m/s, as Figure 5 shows. Salt particles' crystal structure suffers excess flaws at higher temperatures, resulting in a yellow color and leading to decreased NaCl percentage and whiteness. The air velocity was determined to be the critical parameter; therefore, it should be appropriately selected to maximize drying performance and enhance salt particles' quality.

3.3. Effect of Drying Time

The drying times' effect on the salt particles' quality was investigated at 30, 45, 60, 75, and 90 min., as Figure 6 and Figure 7 show.

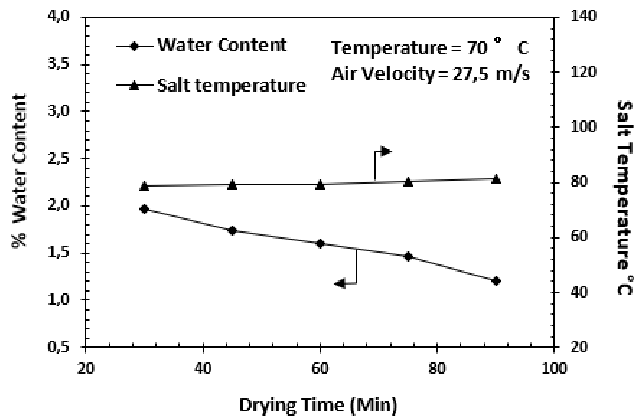

Figure 6 Drying times' effect on salt's water content and temperature

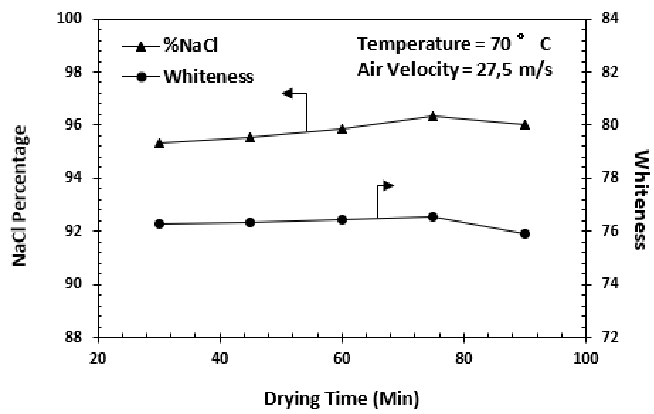

Figure 7 Drying times' effect on NaCl percentage and whiteness

The temperature and air velocity were kept constant at 70°C and 27.5 m/s, respectively. Figure 6 shows that the water content decreased as the salt particles' temperature and the drying time increased. The 30 min. drying time adequately dried the salt particles to less than 2% water content. At drying times of 30–90 min., the NaCl percentage and whiteness increased with drying times to their ultimate values and then decreased. Longer drying times were observed to raise the salt particles' temperature. At drying times beyond 75 min., a yellow color appeared alongside decreases in NaCl percentage and whiteness, as Figure 7 shows.

3.4. Hot Air Performance

This subsection examines the experiments' hot air performance in terms of energy consumption and drying energy efficiency, as Table 2 shows.

Table 2 Energy consumption and energy efficiency for different temperatures, air velocities, and drying times

Variation	Variable	Energy consumption (kWh)	Energy efficiency
Temperature (°C)	50	1.62	0.165
	60	1.71	0.168
	70	1.81	0.166
	80	1.90	0.163
	90	2.01	0.161
Air velocity (m/s)	17.7	1.76	0.160
	20	1.77	0.162
	22.5	1.79	0.166
	24.4	1.80	0.170
	27.5	1.81	0.170
Drying time (min)	30	1.81	0.166
	45	2.71	0.113
	60	3.61	0.086
	75	4.51	0.070
	90	5.42	0.060

Increasing temperatures and drying times increased energy consumption but decreased drying energy efficiency because the energy consumption was directly proportional to the electric current required to increase the heater's temperature and required drying time. However, increasing air velocities improved drying energy efficiency. Increased air velocities consumed less energy than increasing temperatures and drying times, and they more significantly reducing the water content. Increasing drying times to more than 30 min. was unfavorable because most of the water content was determined to have been removed by 30 min., decreasing the drying energy efficiency. Therefore, both temperature and air velocity should be correctly selected to reduce energy consumption and increase drying energy efficiency. An average 1.79 kWh of energy was consumed to produce 5 kg of dried salt from crude solar sea salt at optimum operating parameters with a hot air dryer.

3.5. Salt Quality and Specific Energy Consumption

Salt quality assessments are essential in the production of high-quality salt suitable for industry. Water content, NaCl percentage, and whiteness are required for the food industry. Table 3 compares the results and experimental operating conditions of a fixed-bed hot air dryer (the current study) and a rotary hot air dryer (Han et al., 2019).

Table 3 Operating conditions of a fixed-bed hot air dryer (the current study) versus a rotary hot air dryer (Han et al., 2019)

Description	Present study	Han et al. (2019)
Type of hot air dryer	Fixed-bed	Rotary
Equipment dimension (mm)	600 × 400 × 200	Ø 200 × 248
Rotational speed (rpm)	—	1.0–1.5
Drying temperature (ºc)	50, 60, 70, 80, 90	50, 75, 100
Drying time (minute)	30, 45, 60, 75, 90	10, 20, 30
Initial water content (wb)	11.5%	13.33%
Final water content (wb)	1.73%	4.7%
Initial nacl (%)	91.3	96.5
Final nacl (%)	96.91	98.6
Initial whiteness	72.5	58.5
Final whiteness	77.74	67
Specific energy consumption (kwh/kg)	0.35	0.3

Both studies reported increased salt quality via increased temperatures and drying times up to a certain value. A yellow color appeared at higher temperatures, resulting in low-quality salt. The calculated average increase in NaCl content was 5.61% for the current study, and the removed water content was 9.77%. These values were higher than the corresponding values reported by Han et al. (2019) of 2.1% NaCl content and 8.63% removed water content. However, the previous study reported 8.5-percentage-point higher whiteness than the current study (2.1 percentage points). Thus, the present study's dryer performed better in increasing NaCl content and whiteness. The present study's specific energy consumption was 0.35 kWh/kg of evaporated water. The comparison with Han et al. (2019) also revealed that, for a convective-heat hot air dryer (ChHD) with a unit capacity of 2 kg of solar salt, the specific energy consumption was slightly lower than the current study, at 0.3 kWh/kg of evaporated water. This difference was probably due to the higher power required for the blower in the present study; however, this requirement produced more heat energy, which led to a higher drying rate. Consequently, the previously achieved ChHD drying rate (2.1 g/min.) was lower than the corresponding rate in the current study (16.3 g/min.). Drying rates are a critical factor; dryers with high drying rates are preferable for many industries (Tatemoto et al., 2018), and the use of hot air drying has been reported in many food studies beyond salt production (Liu et al., 2020; Maftoonazad et al., 2020; Taghinezhad et al., 2020). The current study's results underline the advantages of using hot air drying to improve salt quality and reduce energy consumption.

4. Conclusions

This experimental investigation showed that salt's water content decreased with increasing operating parameters, such as temperature, air velocity, and drying time. Increased salt temperatures were associated with increased operating parameters. At several given operating parameters, the salt's NaCl percentage and whiteness initially increased to an optimum value and then decreased. Temperature, air velocity, and drying time were found to be critical parameters for hot air drying; therefore, they should be correctly selected for better salt quality. This study also found that, by correctly setting a parameter, the energy required to produce 1 kg of dried salt (NaCl of 96.91% and whiteness of 77.74) from crude solar sea salt was 0.358 kWh. This result shows that hot air dryers are economical for drying high-water-content salt to enhance its quality.

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