Design and performance evaluation of a geothermal dryer for maize drying

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Abstract: Exploiting geothermal energy to dry crops needs a properly designed geothermal crop dryer that is sized to meet the drying requirements of the crops to be dried. This study designed and fabricated a geothermal maize dryer that was tested to determine the drying time required to drying maize grains to 13% w.b. (wet basis) moisture content at Menengai Geothermal Project site within Nakuru County, Kenya. The main components of the geothermal dryer comprised of a dryer cabinet, heat exchanger, and fan unit. Once the air used for maize drying was heated by the heat exchanger, the sized fan unit blew hot air across the maize grains. Geothermal water from a discharging well within the project site supplied the heat to the sized heat exchanger. The designed geothermal maize dryer cabinet had dimensions of 0.55 m × 0.25 m × 1 m with 40 kg drying capacity, a 0.035 kW axial fan with a 0.035 kW motor, and a heat exchanger with an overall heat transfer coefficient of 86.8 W m^{-2} K^{-1}. The experimental results of the designed geothermal dryer showed that increasing the drying air temperature and drying air velocity inside the dryer resulted in reducing the total drying time while increasing the grain layer depth resulted in increased drying time. Experimental results revealed that the shortest drying time required to reduce the moisture content of maize from 19.3% w.b. to 12.9% w.b. was 4 ½ hours, achieved using a drying air temperature of 45 ℃, a drying air velocity of 0.5 m s^{-1}, and a grain layer depth of 0.15 m. This is significantly lower than the average of 5 days it takes to dry maize in open-sun drying.

Keywords: geothermal dryer, maize drying, dryer cabinet, heat exchanger, fan unit, drying time

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1 Introduction

Drying agricultural products is a traditional method for preserving various foods like grains, meat, and fish. Since most farm products are not consumed immediately after harvesting, post-harvest processing such as drying is necessary (Popovska-Vasilevska, 2003). Food drying helps to lower the moisture content of the food products, which provides numerous benefits such as extended shelf life, minimized risk of aflatoxin formation, and decreased mold growth. It also helps in reducing transportation and storage costs.

In general, the drying process involves the transfer of heat and mass water. The drying air is heated and then blown over the product to be dried. The heat then conducts inward through the product, which raises the temperature of the product continuously until the moisture at the product surface starts to evaporate. As the heated air continuously blows over the product to be dried, it absorbs moisture from the surface of the product and carries it away, maintaining a constant supply of dry air for

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further evaporation (Jayaraman and Gupta, 2006).

Maize is a major staple food in Kenya; however, major post-harvest losses occur between harvesting and consumption mainly due to insufficient drying (Groote et al., 2019). According to Gitonga et al. (2013), harvested maize has a high moisture content of 20%-25% wet basis (w.b.), which makes it susceptible to damage from fungi and insects. Therefore, drying maize is a crucial step in preserving it for extended storage periods without any harm (Folaranmi, 2008). When maize is dried to a moisture content of 13% w.b., it can be safely stored, preventing issues like mold growth, insect infestation, and aflatoxin formation (Kinyanjui, 2013). Efficient drying not only minimizes losses and maintains maize quality, contributing to the well-being of the population but also enhances farmers' productivity and maize marketability. As a result, farmers enjoy increased profits, and the country benefits from improved food security.

Majority of farmers in Kenya still use natural sun drying which is only reliable during the sunny seasons and is labor intensive. According to Tonui et al. (2014) Kenya experiences about four effective sun drying hours during the sunny season. This results in an average of 6 days and 4 hours of open-sun drying of a maize sample to reduce its moisture content from 19.3% w.b. to 13.2% w.b. Groote et al. (2019) determined that it took commercial traders between two to seven days to dry a single batch of maize of 90 kg. Kinyanjui (2013) stated that open-sun drying by small scale farmers took between 5 to 45 days to reduce the moisture content to around 13% w.b. Although mechanized drying is being adopted in Kenya, it is still unreliable and expensive since it uses mainly fossils fuels, electricity or solar dryers (Tonui et al., 2014). Therefore, there is need for a more reliable source of heat for maize drying to reduce the drying time and improve grain quality.

Geothermal energy has been identified as one of the best alternatives for crop drying over fossil fuels, electricity, and solar due to its availability throughout the year, minimal harmful emissions, and its relative low cost (Helvacı, 2012). In Kenya, geothermal energy has predominantly been harnessed for electricity generation. However, there exist numerous untapped opportunities for direct utilization, such as crop drying (Mariita, 2010). On a global scale, geothermal energy has been widely employed for crop drying through the use of geothermal crop dryers, effectively drying various crops like tomatoes and cereals (Lund, 2006). A geothermal dryer is used to utilize geothermal energy for crop drying. The main components of the dryer are a dryer cabinet, heat exchanger, and fan unit. The dryer cabinet, where grains are placed for drying, plays a vital role in the process (Tonui et al., 2014). The heat exchanger transfers heat from one fluid to another. The most common heat exchanger designs are counter flow, parallel flow, and mixed flow design with the choice of heat exchanger design depending on factors such as cost, specific application, and heat transfer requirements (Khamala, 2016). Counter flow is mostly preferred due to its higher heat transfer efficiency than the parallel flow design. Mixed flow design uses both principles of counter flow and parallel flow. The fan unit blows the drying air into the dryer cabinet and can be powered by electricity or solar. The choice between axial and centrifugal fans depends on cost and volumetric airflow requirements. Axial fans are more cost-effective but noisier while centrifugal fans are ideal for deep grain levels and high air volumes (Sadaka, 2014). All components need to be sized appropriately to ensure sufficient airflow with minimal energy consumption.

The best range of temperature for drying maize intended for human consumption according to Kinyanjui (2013), Osodo (2018), and Tonui et al. (2014) is between 43℃ and 50℃. The air velocity also plays a critical role in maize drying, with a velocity range of 0.2 to 0.5 m s^{-1} having been researched in different studies (Kinyanjui, 2013; Tonui et al., 2014). Another important factor in maize drying using a crop dryer is grain layer depth. According to Jayaraman and Gupta (2006), the grain layer depth is determined by one of the two methods of crop drying; thin-layer or deep bed drying. The thin-layer drying assumes uniform temperature distribution, while deep bed drying takes into account variations in air conditions at different grain depths and times (Jayaraman and Gupta, 2006; Kinyanjui, 2013). Thin-layer drying has a thickness of up to 0.20 meters and has a higher drying rate than deep bed drying due to the consistent drying air conditions that prevail uniformly across the entire grain mass and was preferred for this research.

2 Materials and methods

2.1 Design of the geothermal dryer components

The geothermal maize dryer was specifically designed to accommodate 40 kg of maize grain. To simplify the loading process and eliminate the need for mechanical lifting equipment, the batch was divided equally into two trays, with each tray holding 20 kg of maize grain. This division allowed for convenient and manual loading onto the dryer, making the operation more user-friendly.

2.1.1 Cabinet dryer design

The cabinet dryer is used to hold the trays where the maize grains were placed inside the dryer. It was constructed using 16-gauge sheet metal while the trays were constructed using mesh wire to allow for air flow. The size of the cabinet dryer was determined by the dimensions of the trays to be placed inside the dryer. The dimension of both trays was determined by the batch of maize grains placed in each tray which was used to calculate the volume of the maize grains and the cross-sectional area of the trays.

(1) Volume per tray

The volume per tray, V_{gr} (m^{-3}) was determined by the mass and density of the maize grains (Stephen and Emmanuel, 2009):

$$V_{gr} = \frac{m_{gr}}{\rho_{gr}} \quad (1)$$

Where

ρ_{gr}= maize density (kg m^{-3})

m_{gr}= mass of maize for one tray (kg)

(2) Cross-sectional area of the cabinet dryer

The cabinet dryer cross-sectional area, A_{dc} (m^2) was determined from Equation 2 (Stephen and Emmanuel, 2009):

$$A_{dc} = \frac{V_{gr}}{L_{gr}} \quad (2)$$

Where

L_{gr}= grain layer depth (m)

V_{gr}= maize volume for one tray (m^3)

2.1.2 Heat exchanger design

The heat exchanger was used to supply heat used to dry the maize grains. The source of heat for this research was from a pre-existing heat exchanger that used hot geothermal water (brine) to heat fresh water for use in the other direct use projects on the site. The counter flow design was chosen because it transfers the most heat from the geothermal-heated water to the air. During the design process, steady-state conditions and negligible heat losses were assumed. Several important parameters were calculated to ensure optimal performance of the heat exchanger. These calculations included determining the rate of heat transfer, evaluating the logarithmic mean temperature difference (LMTD), the overall heat transfer coefficient, and calculating the required surface area of the heat exchanger to achieve efficient drying of the maize grains.

(1) The rate of heat transfer

The law of conservation of energy was used to determine the rate of heat transfer, $\dot{Q}$ (J s^{-1}) (Akpan et al., 2016):

$$\dot{Q} = \dot{m}_w C_{pw}(T_{b2} - T_{b1}) = \dot{m}_a C_{pa}(T_{a1} - T_{a2}) \quad (3)$$

Where

C_{pw};C_{pa} = water and air specific heat capacity respectively (J kg^{-1} ℃$^{-1}$)

$\dot{m}_w$;$\dot{m}_a$ =water and air mass flow rate respectively (kg s^{-1})

T_{a1}= temperature of the geothermal-heated water at heat exchanger entry (℃)

T_{a2}= temperature of the geothermal-heated water at heat exchanger exit (℃)

T_{b1}= temperature of air at dryer entry (℃)

T_{b2}= temperature of air at dryer exit (℃)

(2) Logarithmic mean temperature difference (LMTD)

The LMTD, ΔT_{LM} provides an average temperature difference between fluids with different temperatures at the heat exchanger inlet and outlet which helps determine the heat exchanger effectiveness in transferring heat between the two fluids (Khamala, 2016). It is determined using Equation 4:

$$\Delta T_{LM} = \frac{(T_{a1} - T_{b2}) - (T_{a2} - T_{b1})}{ln(\frac{T_{a1} - T_{b2}}{T_{a2} - T_{b1}})} \quad (4)$$

(3) Overall heat transfer coefficient

The convective and conductive heat transfer equations are used to determine the overall heat transfer coefficient, U (W m^{-2} K^{-1}) (Twidell and Weir, 2015):

$$\frac{1}{U} = \frac{r_2}{r_1 h_1} + \frac{r_2}{k}\ln(\frac{r_2}{r_1}) + \frac{1}{h_2} \quad (5)$$

Where

r_1= internal diameter of the heat exchanger tube (m)

r_2= external diameter of the heat exchanger tube (m)

h_1=geothermal-heated water heat transfer coefficient (W m^{-2} K^{-1})

h_2= air heat transfer coefficient (W m^{-2} K^{-1})

k= thermal conductivity of tube material (W m^{-1} K^{-1})

(4) Heat exchanger surface area

The heat exchanger surface area, A_s is determined using Equation 6 (Khamala, 2016):

$$A_s = \frac{\dot{Q}}{\Delta T_{LM} U} = \pi DL \quad (6)$$

Where

D= diameter of the heat exchanger tube (m)

L= length of the heat exchanger tube (m)

2.1.3 Design of the fan unit

The role of the fan unit was to blow the heated drying air over the maize grains to effect drying. The fan unit design was based on specific amount of moisture needed to be extracted from the grains to achieve 13% w.b. moisture content and the volume of air needed to carry away this moisture during the drying process.

(1) Amount of moisture to be extracted

The moisture to be extracted from the maize, M_w (kg) was determined using Equation 7 (Akpan et al., 2016):

$$M_w = M_i \frac{(mc_{wbi} - mc_{wbf})}{(1 - mc_{wbf})} \quad (7)$$

Where

M_i= initial mass of the maize (kg)

mc_{wbi}= initial maize moisture content (% w.b.)

mc_{wbf} = final maize moisture content (% w.b.)

(2) Air needed for maize drying

The quantity of air needed to effect maize drying, M_a was determined using Equation 8 (Tonui et al., 2014):

$$M_a = \left|\frac{M_w}{RH_f - RH_i}\right| \quad (8)$$

Where

RH_i; RH_f = initial and final humidity of air respectively (%)

Volume of air need for maize drying

The air volume needed to dry the maize, Va was determined by Equation 9 (Khamala, 2016):

$$V_a = \frac{M_a}{\delta} \quad (9)$$

Where

δ= density of air (kg m^{-3})

(3) Mass flow rate

The air mass flow rate needed to dry maize, $\dot{m}_a$ was determined using Equation 10 (Akpan et al., 2016):

$$\dot{m}_a = \delta \times u_{0air} \times A_{dc} \quad (10)$$

Where

u_{0air}= air velocity (m s^{-1})

A_{dc}= dryer cabinet cross-sectional area (m^2)

(4) Pressure drop across the drying tray

Ergun's equation helps calculate the drop in pressure across the dryer trays where the maize grains were placed. The pressure drop, ΔP was determined using Equation 11 (Jia et al., 2015):

$$\frac{\Delta P}{L_p} = \frac{150\mu(1-\varepsilon)^2 u_0}{\varepsilon^3 d_p^2} + \frac{1.75(1-\varepsilon)\rho\mu^2}{\varepsilon^3 d_p} \quad (11)$$

Where,

L_p= drying bed length (m)

μ= fluid viscosity (kg m^{-1} s^{-1})

ε= void space (ratio of empty volume of cabinet to total volume of cabinet)

u_0= fluid velocity (m s^{-1})

ρ= fluid density (kg m^{-3})

dp= grain diameter (m)

(5) Quantity of heat provided by the geothermal-heated water

The quantity of heat provided, Q_{gb} was determined by Equation 12 (Kinyanjui, 2013):

$$Q_{gb} = \dot{m}_w C_{pw}(T_{b2} - T_{b1}) \quad (12)$$

Where

$\dot{m}_w$ = geothermal-heated water mass flow rate (kg s^{-1})

C_{pw}= geothermal-heated water specific heat capacity (J kg^{-1} ℃$^{-1}$)

(6) Fan power

The fan power, P_f was determined using Equation 13 (Wilcke and Morey, 2015):

$$P_f = \frac{\dot{V} \times P_s}{6356 \times \eta_f} \quad (13)$$

Where

$\dot{V}$ = air volume flow rate (cfm)

P_s= static pressure (inches of water)

η_f= fan power efficiency (%)

2.2 Experimental procedure

After dry testing the maize dryer without load, maize grains were loaded into the dryer cabinet. The ambient temperature, inlet and outlet temperatures of the drying air, were measured using the respective measuring instruments and recorded. The moisture content and time taken for the maize were measured at 30-minute intervals until a moisture content of 13% w.b. was achieved. The levels in Table 1 were used in the experiment and were based on previous research by Kinyanjui (2013), Osodo (2018) and Tonui et al. (2014).

Table 1 Parameters used to evaluate geothermal dryer performance parameters and their levels

Factor	Parameter	Units	Level 1	Level 2	Level 3
A	Drying air temperature	℃	40	45	50
B	Drying air velocity	m s^{-1}	0.2	0.35	0.5
C	Grain layer depth	m	0.10	0.15	0.20

Table 2 Performance evaluation of the sized geothermal dryer

A		Effect of Drying air temperature	
Experiment	Air temperature (℃)	Air velocity (m s^{-1})	Grain layer depth (m)
1	40	0.35	0.15
2	45	0.35	0.15
3	50	0.35	0.15
B		Effect of Drying air velocity	
Experiment	Air temperature (℃)	Air velocity (m s^{-1})	Grain layer depth (m)
4	45	0.2	0.15
5	45	0.35	0.15
6	45	0.5	0.15
C		Effect of Grain layer depth	
Experiment	Air temperature (℃)	Air velocity (m s^{-1})	Grain layer depth (m)
7	45	0.35	0.1
8	45	0.35	0.15
9	45	0.35	0.2

To determine the effect of every parameter, each parameter was varied from Level 1 to Level 3 while the other two parameters were held constant to isolate the effect of that single parameter on the outcome of the experiment. In this way, the specific effect of each parameter on the outcome of the experiment was determined. The levels to be used for the constant values were selected based on the typical values from previous experiments. For temperature, Khamala (2016) and Kinyanjui (2013) found that the best temperature for maize drying for human consumption as 43℃. Therefore, 45℃ was selected since it was the closest value to 43℃ as determined by the two researchers. For air velocity, Kinyanjui (2013) and

Tonui et al. (2014) determined an air velocity range of 0.2 to 0.5 m s^{-1} as effective for thin-layer drying. Therefore, the air velocity selected was 0.35 m s^{-1} since it was the average value in both studies.

Finally, to determine the constant value for grain layer depth, the maximum depth for thin-layer drying of 0.20 m was used (Jayaraman and Gupta, 2006). Kinyanjui (2013) in his design of a geothermal grain dryer used maximum grain depth of 0.1 m for each tray. Therefore, the average value of 0.15 m was selected for this research. The experiments were conducted as indicated in Table 2.

3 Results

3.1 Designed geothermal dryer

The calculated dimension of the two trays was 0.55 m length, 0.25 m width, and 1m length. The overall dimensions of the dryer cabinet were determined from the tray dimensions as 0.55 m length, 0.25 m width, and 1m length. The cabinet had two trays that were spaced by a height of 0.2 m with a space of 0.2 m from both the top and bottom sections of the cabinet respectively to allow for air movement. The schematic diagram of the designed geothermal dryer is shown in Figure 1.

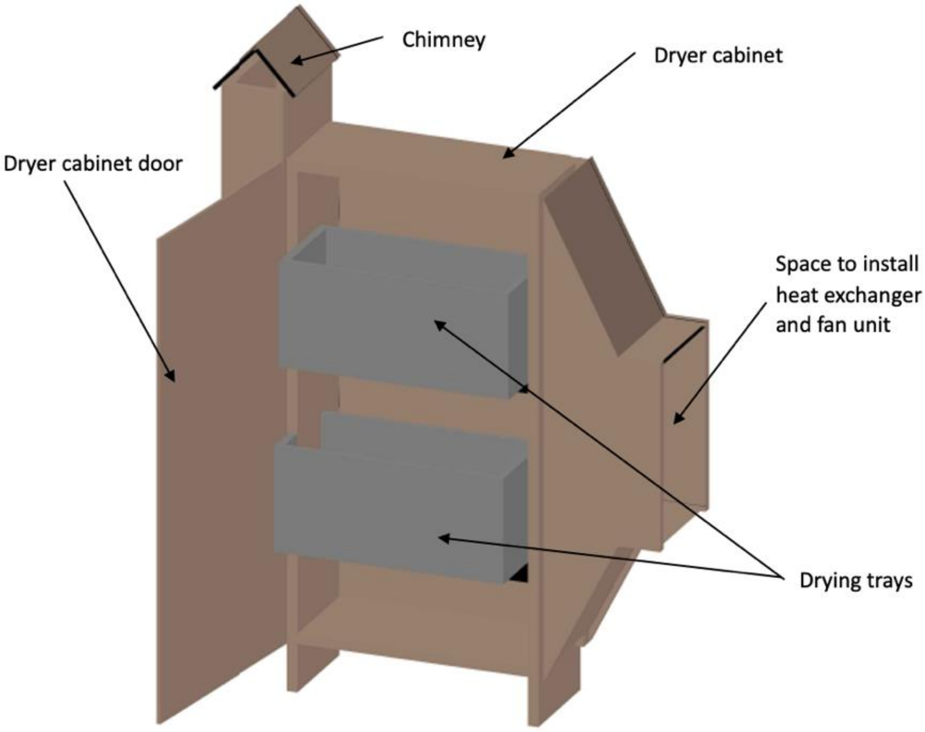

Figure 1 Engineering drawing of the geothermal maize dryer

From calculations, the heat exchanger dimensions were copper tube with a length of 34 m, an internal diameter of 0.02 m and a thickness of 0.0025 m with an overall heat transfer coefficient of 86.8 W m^{-1} K^{-2}. Fins were added to heat exchanger to improve its heat transfer capacity. The minimum fan power required was a 0.0014 kW axial fan. A 0.035 kW fan that was readily available was selected and its speed was regulated using a voltage regulator.

3.2 Assembled geothermal maize dryer

The geothermal cabinet of the dimensions 0.55 m (Length) × 0.25 m (Width) × 1 m (Height) was fabricated using 16-gauge sheet metal with a chimney to allow wet air to flow out of the cabinet. The axial fan and heat exchanger housing were also fabricated using the 16-gauge sheet metal which were secured with nuts and bolts to the cabinet for easy installation and maintenance of the heat exchanger and fan. The designed cabinet trays were fabricated with wire mesh to increase air flow and were designed to be removable to allow for easy loading and unloading of the maize grains as shown in Figure 2. The fluid flow and configuration of the components is shown in Figure 2.

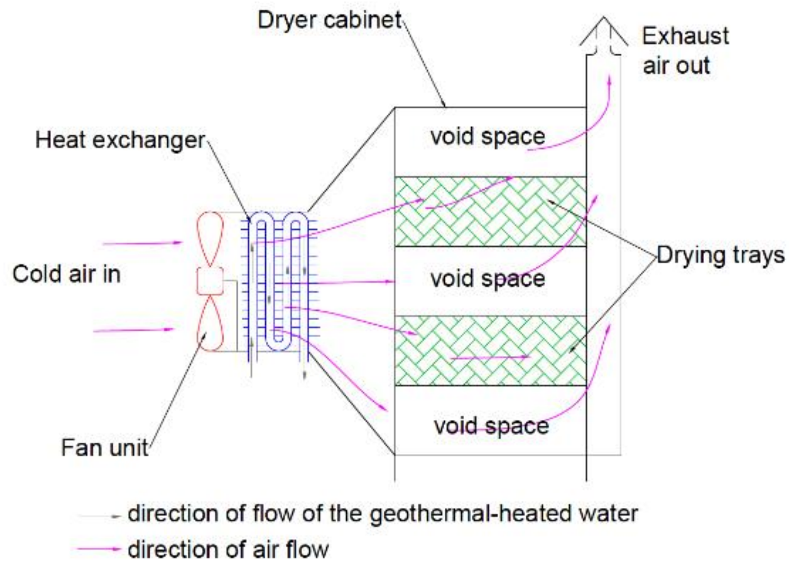

Figure 2 The fluid flow and location of geothermal maize dryer components

3.2 Effect of drying air temperature, air velocity and grain layer depth on drying time

3.2.1 Drying air temperature

To test how drying air temperature affected the drying time, three experiments were conducted as in Table 2 for the three experiments and the results presented in Figure 3. The results in Figure 3 indicated that for the three different drying air temperatures, there was reduction in moisture content as drying time increased. The least drying time required to achieve 13% w.b. moisture content was 300 minutes (5 hours) which was achieved at air temperatures of 45 ℃ and 50 ℃. As the drying air temperature was increased from 40 ℃ to 45 ℃, the drying time reduced by 30 minutes. When the drying air temperature was increased from 45 ℃ to 50 ℃, there was no reduction in the drying time as both the recorded drying times were similar.

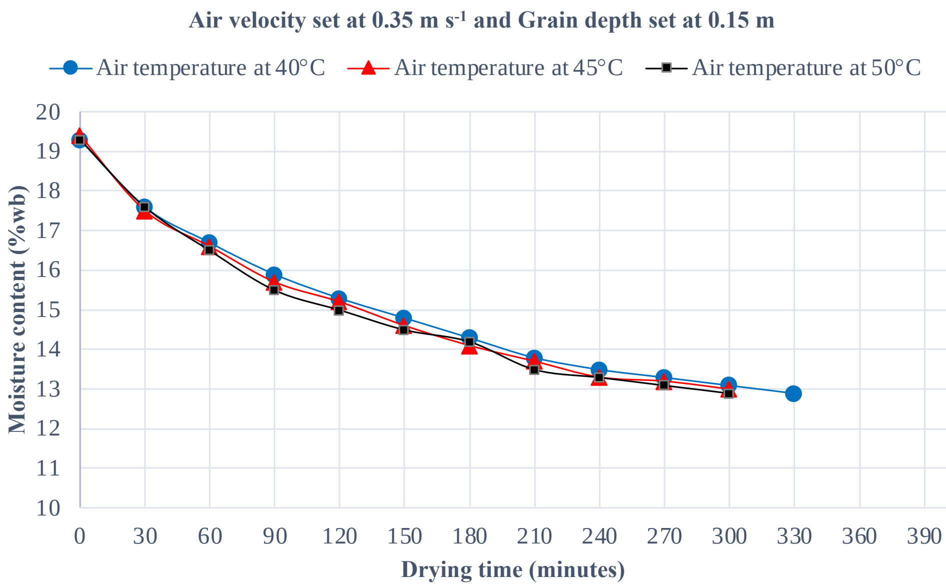

Figure 3 The moisture content variation of the maize with drying time at the three experimental drying air temperatures

3.2.2 Effect of air velocity

To test how drying air velocity affected the drying time, three experiments were conducted as in Table 2 for the three experiments and the recorded results plotted in Figure 4. The results showed that for the three different drying air velocities, the moisture content reduced as drying time increased with the least drying time of 270 minutes (4 ½ hours) achieved with an 0.5 m s^{-1} air velocity while maximum drying time of 330 minutes (5 ½ hours) was achieved with

0.2 m s-1air velocity.

3.2.3 Effect of grain layer depth

To test how grain layer depth affected the drying time, three experiments were conducted as in Table 2 for the three experiments and the recorded results plotted in Figure 5. These results indicate that as the grain depth is increased, the drying time increases because when the depth is smaller, there is lesser static pressure needed to move the air through the maize grains than when the depth is larger. Similar drying times of 300 minutes (5 hours) were achieved with grain depths of 0.15 m and 0.2 m while minimum drying time of 270 minutes (4 ½ hours) was achieved with a grain depth of 0.1 m.

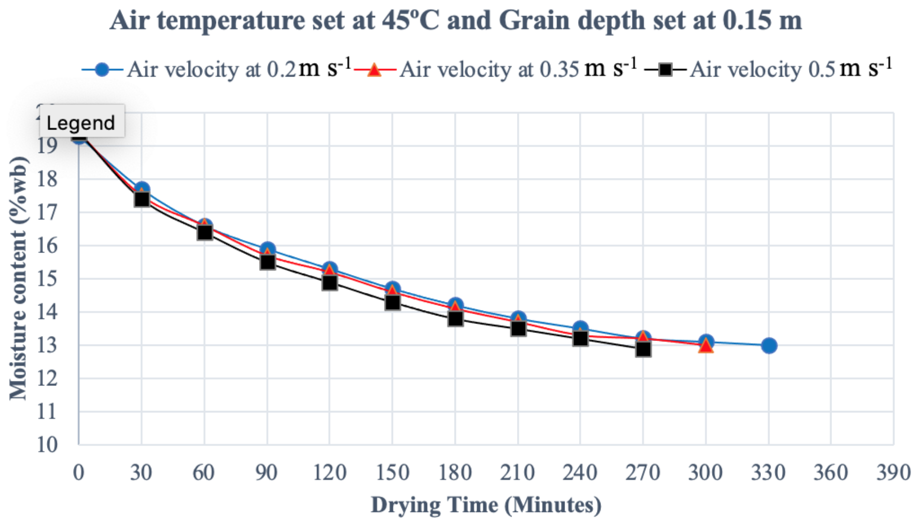

Figure 4 The moisture content variation of the maize with drying time at the three experimental drying air velocities

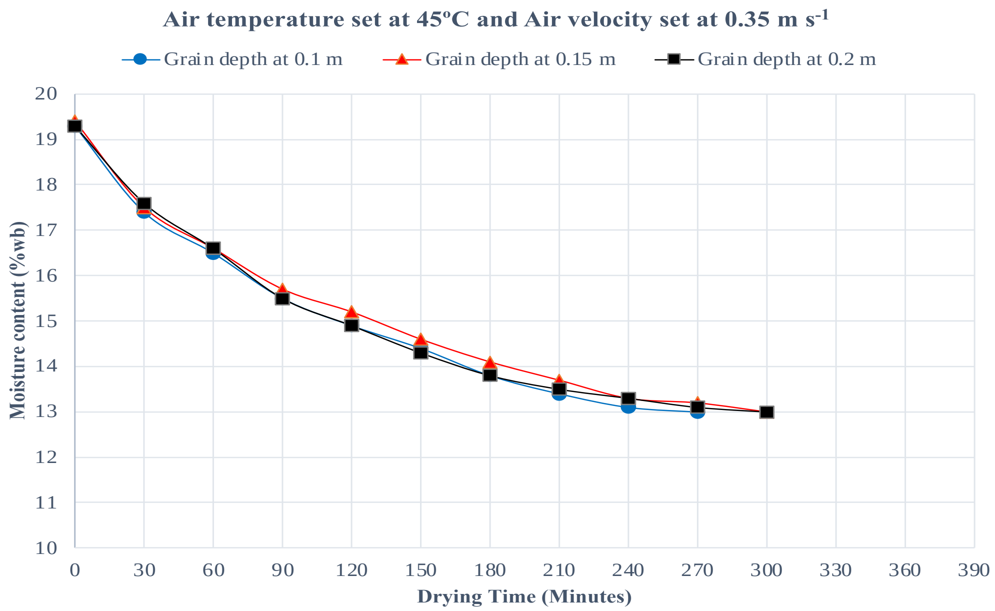

Figure 5 The moisture content variation of the maize with drying time at the three experimental grain layer depths

4 Conclusion

A geothermal maize dryer was designed and evaluated for drying maize grains in Menengai Geothermal Project Site in Nakuru County weather conditions. The dryer reduced the moisture content of maize grains to 13% w.b. moisture content from an average of around 20% w.b.

The dryer's performance was evaluated based on its drying time with the control parameters being drying air temperature, drying air velocity, and grain layer depth. Analysis of drying air temperature effect on the drying time showed that an increase in the from 40 ℃ to 45 ℃ led to reduction in the drying time by 30 minutes, however, increasing it from 45 ℃ to 50 ℃ there was no change in total drying time.

Analysis of the effect of drying air velocity on drying time showed that increasing the drying air velocity reduced the total drying time. The least drying time of 4 ½ hours was achieved at an air velocity of 0.5 m s^{-1}. The experiments evaluating the effect of grain layer depth on the drying time determined that at 0.1 m depth, the total drying time was 4 ½ hours. When the grain layer depth was increased to 0.15 m, the total drying time increased to 5 hours. Further increase in the grain layer depth to 0.2 m did not change the total drying time which remained at 5 hours. Therefore, the minimum drying time of 4 ½ hours was achieved with a grain depth of 0.1 m.

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