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Innovative Low-Cost Naturally Ventilated Maize Seed Storage System

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Abstract

A 22-m^3 residential room was converted to a seed storage facility by retrofitting a solar collector on the roof. Three different chimney sizes of diameter and height of 200 mm x 3.6 m, 200 mm x 4.8 m, 300 mm x 3.6 m and 300 mm x 4.8 m were investigated to determine the best size of the chimney to be used for ventilation in a storage facility. The parameters measured were the air velocity in the chimney duct, as well as the air temperature and relative humidity at the inlet, centre and outlet of the storage facility. The diameter of the chimney had a significant effect ($P<0.05$) on the ventilation rate achieved in the storage facility. Significant differences were found between the different chimney diameters and heights ($P\leq0.05$). The 300 mm diameter chimneys were able to extract hot air from the roof solar collector; however, the 200 mm diameter failed. The modified naturally-ventilated seed storage room was able to reduce the relative humidity from 69.7% to a safe relative humidity of 37.9%, while at the same time the temperature increased from 23.3℃ to 35℃ in the 300 mm x 4.8 m chimney.

Keywords: Seed storage room; Chimney height and diameter; Ventilation rate; Temperature; Relative humidity.

1. Introduction

Historically, chimneys are predominantly used to ventilate buildings and to remove exhaust gases from the fireplace. Solar chimneys are able to generate electricity and to ventilate buildings [1]. These chimneys use the principle of thermal buoyancy requiring that some part of the chimney be made of a solar collector for optimum harvesting of solar radiation. The solar collector heats the air inside the chimney, causing the temperature difference between the air inside the chimney and the air outside the chimney [2]. Passive stack ventilation works well when the indoor temperature is higher than the outdoor temperature. However, the solar chimney still induces ventilation effectively, even when the outdoor temperature is equal to, or higher than, the indoor temperature [3]. A simpler way of making solar chimneys is by merely painting the body surface of the chimney black. The black surface then absorbs and stores heat resulting in increased temperature inside the chimney. The temperature difference causes the hot air to rise, which leads to the upward movement of air, and in this way, ventilation in the building is achieved [4]. There are horizontal and vertical solar chimneys; and according to [5], vertical chimneys increase the ventilation rate up to 22 times, compared to horizontal chimneys. Huynh [6], alludes to this by reporting that solar chimneys attain the maximum flow rate when in vertical position. The effect of a solar chimney on ventilating residential buildings was investigated by Mekkawi and Elgendy [7] in Alexandria, Egypt. Their study revealed that solar chimneys decreased the average room temperature and improved the average indoor velocity by 50%. Lal, *et al.* [8] investigated the ventilation rate induced by a solar chimney, with a height of 4.57 m in a 510-m^3 room and obtained ventilation rates ranging between 5.77 to 7.77 ACH. Solar chimneys generally improve the indoor environment through natural ventilation [9-12].

Tan and Wong [13], reported that solar chimney system worked well in ventilating a three-story building and that they are effective in hot and humid climates and even in cooler days. A study carried out by Khedari, *et al.* [14], the solar chimney was used to reduce the internal heat gain in a 25-m^3 room revealed that solar chimneys were good for circulating the air inside the structure. The achieved air change rate per hour was 8-15 ACH. Bassiouny and Koura [15], showed that changing the solar chimney size has more effect on the airflow and air change rate than changing the inlet size in the ventilated structure. Increasing the inlet by three-folds resulted in an 11% increase in the air change rate, whereas increasing the outlet by the same factor resulted in a 25% increase in the air change rate. Alzaed and Mohamed [9], studied the solar chimney and focused on the effect of inlet area, the chimney width and height and incident solar radiation on the ventilation rate that was induced in the building, using a building prototype. The chimney widths considered were in a range of 5-30 mm and 8-50 mm, for chimney heights, 200 mm and 400 mm, respectively. The optimum width was found to be 12 mm for a 200 mm height and 24 mm for a 400 mm height. Beyond this width, the ventilation rate decreased, and a further increase in the width resulted in a backflow. Increasing the outlet (chimney area) was found be more effective than increasing the inlet in relation to ventilation rates achieved. Bassiouny and Koura [15], obtained similar results where doubling the chimney height from 200 mm to 400 mm resulted in the doubling of the ventilation rate. From this work, it was concluded that increasing the height is an effective way of improving the ventilation rate in a building. Ali [16], also found that increasing the height of the solar chimney enhances its performance. It is not only the height of the solar chimney that influences the ventilation rate, but the cross-sectional area also affects the ventilation rate greatly [7]. Alzaed and Mohamed [9], carried out a study on the performance of the solar chimney by changing the width from 5 cm to 10 cm and the results showed that better ventilation rates were achievable with a width of 5 cm. A width of 10 cm gave a low ventilation rate, since it was beyond the optimum width. Li, *et al.* [17], investigated the following parameters of the solar chimney, namely, the height, width, cavity width, as well as the ratio of the outlet to inlet area, and lastly the outlet location of the solar chimney, using computational fluid dynamics (CFD), fluid flow and MITFLOW models. The length, width (B), height (H), the ratio of outlet area to inlet area A_r and the cavity width (B/H), had the following ranges, 0.5 – 5 m, 0.1 – 0.5 m, 2 – 5 m, 0.6 – 1 m, 0.05 – 0.25, respectively. The study showed that there is an optimum cavity width and solar chimney width that correspond to the maximum ventilation rate, and when the height is increased, the ventilation rate increases. This is in agreement with the results obtained by [15, 16, 18-20]. In addition, the results revealed that optimised ventilation rate is achieved when the inlet area is equal to outlet area. The chimney height and width have a significant impact on natural ventilation, according to Hassanein and Abdel-Fadeel [21].

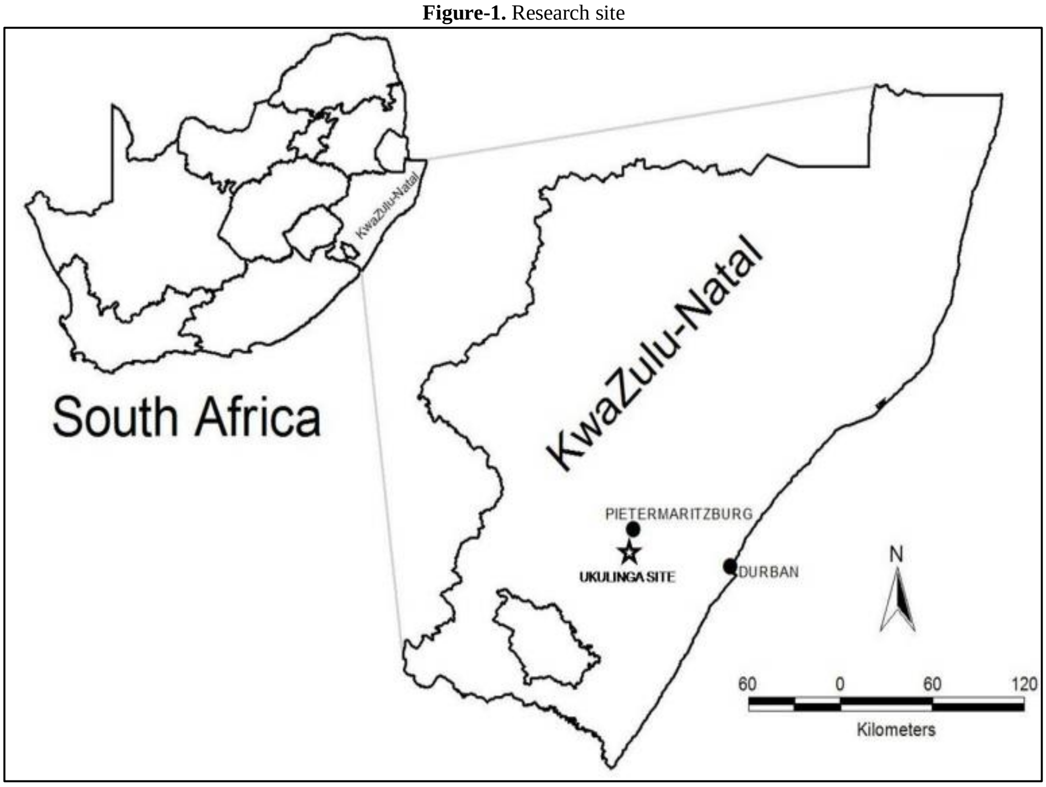
In the sited cases, solar chimneys were used to ventilate structures like residential buildings. This provides a platform for investigating the performance of the solar chimney in other areas, such as the naturally ventilated seed storage facilities. In this case, the storage facility will consists of the solar collector on the roof, for heating the incoming air into the storage room and to reduce the relative humidity. Therefore, the objective of this study is to develop a naturally ventilated seed storage room by investigating the performance of different solar chimney sizes subjected to the same load of maize seeds. The study will focus on both the diameter (cross sectional area) and the height of the chimney as parameters for defining the size of the chimney. In addition, these parameters are crucial in the design of the solar chimney [8, 22, 23]. The performance will be evaluated by looking at the temperature and relative humidity profiles inside the storage facility and the ventilation rate that is achieved in response to the external environmental conditions.

2. Materials and Methods

2.1. Experimental Site and Climatic Data

The seed storage room was installed at the University of KwaZulu-Natal Ukulinga Research Farm, Pietermaritzburg (PMB), South Africa (30º24'S, 29º24'E). The location of the site is shown in Figure 1. It is located at an altitude of 721 m and experiences a mean annual temperature of 18.4℃, with summers ranging from warm to hot and mild winters [24]. The average wind speed in the study site was 0.8 m.s^{-1} during the study period. East-southeast is the prevailing wind direction in the study site [25].

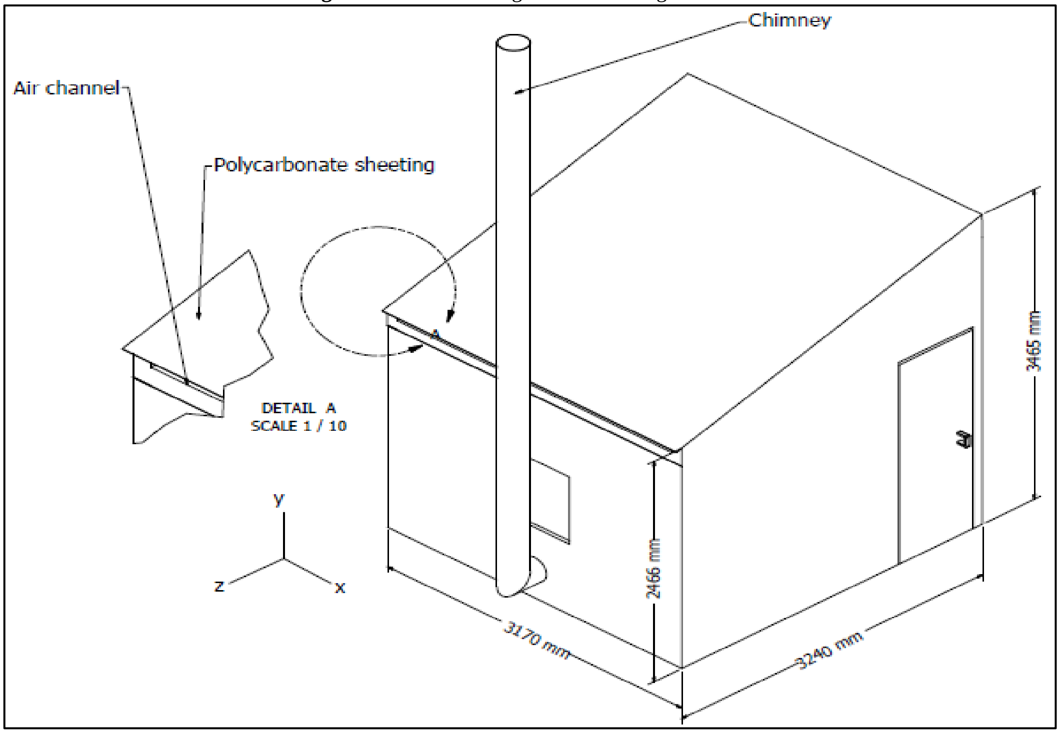
Figure-1. Research site



2.2. Seed Storage System

The seed storage facility had a volume of 22-m^3 as shown in Figure 2 which consists of a roof integrated solar collector for heating the air before it enters the storage room. The solar chimney was manufactured from galvanized steel. The surface of the experimental storage structure was painted black in order to collect direct solar energy to heat the dry air circulation in the grain storage.

Figure-2. Schematic diagram of the storage structure



2.3. Solar Collector

The solar collector consists of clear corrugated polycarbonate sheets and corrugated iron sheets underneath which was installed according to Moummi, *et al.* [26]. The corrugated polycarbonate sheets had a standard thickness of 1 mm, a width of 760 mm and a length of 3.5 m. A mild steel frame made of bars with a cross-sectional area of 3 mm by 50 mm supported these. The corrugated iron sheets under the corrugated polycarbonate sheets were painted black for enhancing the absorption of radiation. A space of 10 cm was left between the polycarbonate sheets and the iron sheets, as an air channel.

2.4. Shelf for Seed Bags

Seed bags were made of a hessian material following the procedures as reported by Adetumbi [27] and stacked on pallets [28]. Each seed sack contained 10 kg of seeds, since the moisture content equilibrates quickly in the seed mass [29].

2.5. Experimental Design

The following combinations of chimney diameter and height were used in this experiment:

(a) 200 mm x 3.6 m,
(b) 200 mm x 4.8 m,
(c) 300 mm x 3.6 m,
(d) 300 mm x 4.8 m.

2.6. Data Collection

The temperature and relative humidity of the indoor and outdoor air, the air velocity in the chimney duct and the solar radiation intensity were recorded during the storage period. The data loggers (Onset HOBO Four Channel USB Temperature/Humidity/Light/External Input Data Logger with 12-bit resolution) were installed at different locations to measure the temperature and relative humidity inside the storage facility. They were positioned at the inlet, the centre of the storage chamber and at the outlet of the system. The control room, which was without airflow, had only two data loggers installed at the centre of the structure and inside the seed bags. The temperature and relative humidity were recorded every minute from 9:00 am until 17:00 pm, on sunny days. The velocity in the chimney duct was measured manually at least every 30 minutes with a Heavy Duty Hot Wire Thermo-Anemometer Airflow Meter. The experiment was carried out over a period of four days, where only sunny days with an average temperature of at least 30ºC were selected. For each day of the experiment, a different chimney size combination was used and only one-hour data with the temperature range of 28-31ºC was selected for data comparison.

2.7. Data Analysis

Analysis of variance, with a 5% level of significance on the data of air temperature, air relative humidity and air velocity in the chimney duct was carried out, using Genstat18.0.

3. Results and Discussion

3.1. Velocity in the Chimney Duct

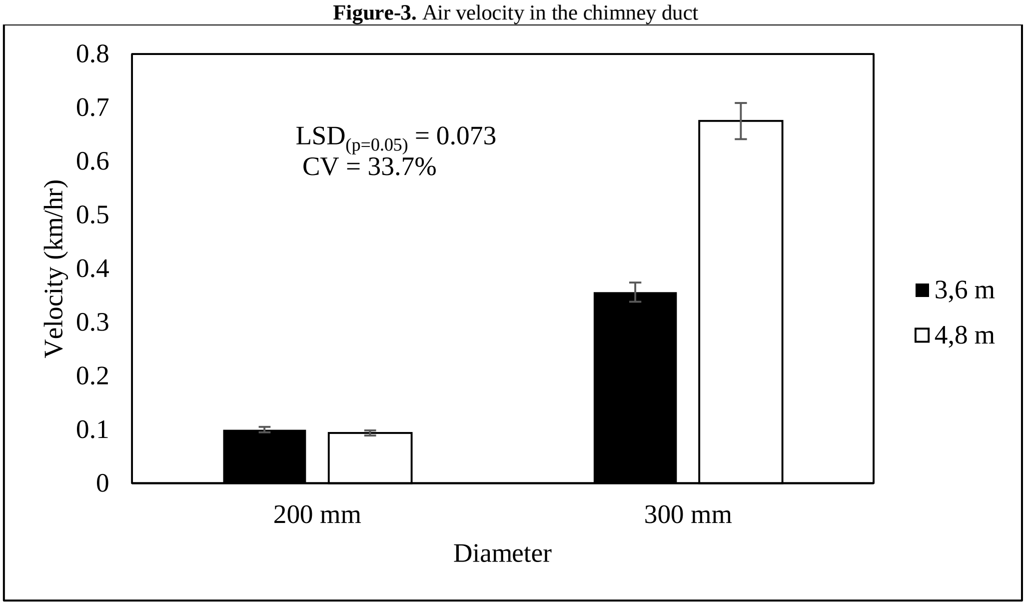
The velocity of the air recorded in the chimney duct was different, depending on the chimney height and diameter sizes. The velocity obtained for 200 mm and 300 mm diameter sizes were significantly different ($P \leq 0.05$) (see Table 1).

Table-1. The results of the inlet, centre and outlet temperature, relative humidity and velocity as a result of different chimney sizes

	Inlet RH (%)	Centre RH (%)	Outlet RH (%)	Inlet Temp (ºC)	Centre Temp (ºC)	Outlet Temp (ºC)	Velocity ($m s^{-1}$)
mean.200mm.3.6m	59.6±0.97	70.9±0.59	71.28±3.57	26.3±0.54	27.8±0.13	23.8±1.05	0.1±0.09
mean.200mm.4.8m	57.2±0.78	70.5±3.35	69.31±0.80	27.8±0.50	27.6±0.23	24.7±0.22	0.094±0.07
mean.300mm.3.6m	13.7±3.01	44.6±0.55	54.3±2.09	46.4±4.87	34.2±0.24	31.8±0.16	0.356±0.1
mean.300mm.4.6m	9.4±1.81	37.9±0.47	45.7±0.53	54.2±2.64	35.7±0.15	31.1±0.53	0.675±0.14
p.value diameter	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
p.value height	<0.001	<0.001	<0.001	<0.001	<0.001	0.021	<0.001
p.value height. Diameter	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	<0.001

Velocity measured for a 200 mm diameter for both chimney heights of 3.6 m and 4.8 m had similar mean velocity values of 0.1 ± 0.09 and 0.094 ± 0.07 $km\,hr^{-1}$, respectively. Extremely low velocities in the solar chimney are the consequence of the reverse flow in the duct [9], which indicates that a chimney diameter of 200 mm is failing to create enough suction to circulate in the storage room. In short, this chimney size induces an insufficient draft to overcome system flow resistance, which is due to chimney flow resistance coefficient being inversely proportional to the diameter; for instance, small diameters result in high resistance [30]. Therefore, increasing the diameter of a chimney will increase the chimney draft. Furthermore, this can also be observed in Figure 3, where the temperatures at all the positions inside the storage room are similar, indicating that air is stagnant [31]. A 300 mm chimney achieved 0.356±0.1 $km\,hr^{-1}$ and 0.675±0.14 $km\,hr^{-1}$, for 3.6 m and 4.8 m heights, respectively. The average air change per hour (ACH) achieved by a chimney with a diameter of 300 mm at heights of 3.6 m and 4.8 m, was 9.2 ACH and 17.4 ACH, respectively. The minimum ventilation rate recommended for stored maize seeds is 0.08 $m^3 min^{-1}$ [32]. However, the achieved ventilation rate was 6.4 $m^3 min^{-1}$ and 3.4 $m^3 min^{-1}$, for heights of 4.8 m and 3.6 m, respectively, with the diameter of 300 mm. Longer chimneys provide more ventilation than shorter ones, due to the large vertical distance from the chimney foot to the outlet of the chimney, which provides an excessive draft [33].

Figure-3. Air velocity in the chimney duct



An improvement in the ventilation rate was observed when the chimney diameter was increased from 200 mm to 300 mm. Similarly, when the height was increased from 3.6 m to 4.8 m, an increase in ventilation rate was also observed (see Figure 3). These findings agree with those of Bassiouny and Koura [15]; Ali [16]; Li, *et al.* [17]; Mathur, *et al.* [18]; Yan, *et al.* [20]; Mehani and Settou [19]. A huge change in the ventilation rate was observed when the chimney diameter was changed, compared to when the chimney height was changed. Changing the diameter from 200 mm to 300 mm, for the same height of 4.8 m, changed the ventilation rate from 0.89 $m^3 min^{-1}$ to

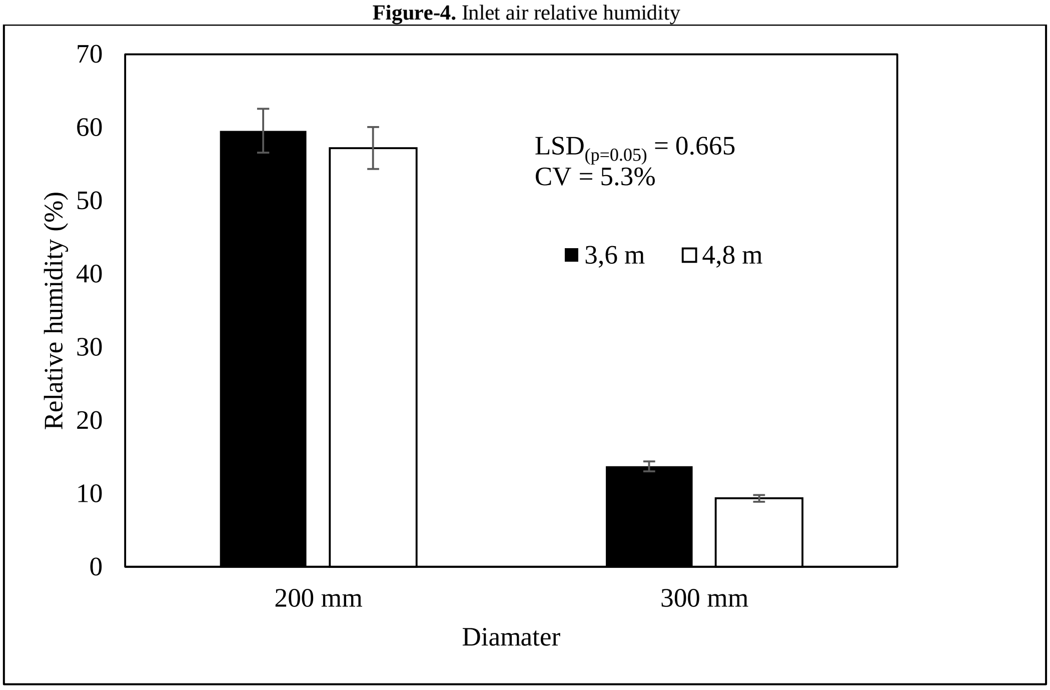
6.4 $m^3 \cdot min^{-1}$. Afonso and Oliveira [34], Bassiouny and Koura [15] and Tan and Wong [13] reported that the cross-sectional area (diameter) in the design of the solar chimney has a stronger effect on the ventilation rate and airflow pattern than the chimney height. When the chimney cross-sectional area is increased beyond its optimum size, reverse flow begins to take place in the solar chimney and this results in a reduction in the ventilation rate [9, 15, 35, 36]. From the current study, the optimum diameter was not reached, since 300 mm gave a higher ventilation rate than the 200 mm chimney. However, the chimney size that performed better than the rest in the current study was that with a 300 mm diameter and a height of 4.8 m.

3.2. Relative Humidity at the Inlet

The storage facility operates by heating the ambient air before it enters the indoor environment in the solar collector on the roof. The duty of the chimney is to suck in the heated air from the roof solar collector, down to the indoor environment and out through the duct. The results from the experiment revealed that a 300 mm diameter chimney induced a significantly lower ($P \leq 0.05$) relative humidity in the inlet than a 200 mm diameter chimney. A lower relative humidity was attainable with a chimney height of 4.8 m, compared to a chimney height of 3.6 m ($P \leq 0.05$). When the heights are combined with a diameter of 200 mm, the results show a high relative humidity, compared to when the heights are combined with 300 mm chimney (see Figure 4). The initial temperature and relative humidity in the storage room were 23.3℃ and 69.7%. For a 200 mm diameter chimney, the relative humidity decreased by 10.1% and 12.5%, for 3.6 m and 4.8 m chimney heights, respectively. However, for a 300 mm diameter chimney, the relative humidity decreased drastically by 56% and 60.3%, relative to the initial relative humidity, for 3.6 m and 4.8 m chimney heights, respectively. The change in relative humidity is dependent on the change in temperature of the air heated by the solar collector, with high temperatures resulting in a low relative humidity, and vice versa [37-39]. The reason why the relative humidity decreased drastically for the 300 mm diameter chimney for all heighs (3.6 and 4.8 m), is because this size is capable of extracting hot air from the roof solar collector and driving it to the storage enviromnent, which eventually changes the storage conditions. On the other hand, the 200 mm diameter chimney had a slight reduction in relative humidity, this is because it is incapable of extracting hot air from the solar collector. This slight reduction in relative humidity was caused by the pressure that developed in the roof solar collector, due to thermal convection of hot air rising along the roof slope and the wind pressure pushing the heated air into the inlets. Therefore, hot air was reaching the inlets intermittently, resulting in a slight reduction in relative humidity, as opposed to the case of 300 mm diameter where hot air was extracted continuously, resulting in constantly high temperatures.

For the same diameter, a height of 4.8 m always gives lower relative humidity than a height of 3.6 m (see Figure 4). The results imply that a bigger diameter draws the air better from the solar collector than a smaller diameter. Moreover, the longer the chimney, the better the performance of the chimney, in driving hot air into the storage indoor environment from the solar collector. Air heated by the solar collector has a low relative humidity. From the previous studies, the focus has been on the solar chimneys with a rectangular cross-section, where the width of the solar chimney was varied to assess the effect of cross-sectional area. The effect of height was also investigated. The current study investigates the effect of changing the chimney diameter, which directly reflects the cross-sectional area of the solar chimney. Yan, *et al.* [20] and Guo, *et al.* [40] showed that the increasing chimney height and cross-section, as defined by the width, improves its performance. This agrees with the results obtained in the current study. A chimney with a height of 4.8 m and a diameter of 300 mm performed better than the rest of the chimney sizes explored.

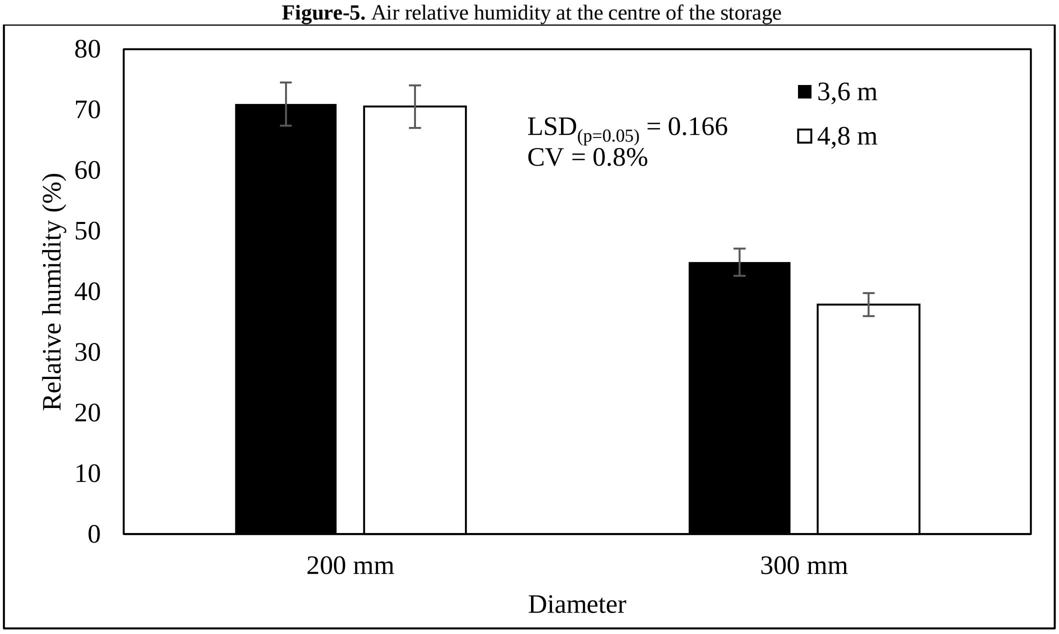
Figure-4. Inlet air relative humidity



3.3. Relative Humidity at the Centre

The relative humidity in the storage centre with 300 mm diameter chimney was found to be lower than that with a 200 mm chimney diameter ($P \leq 0.05$) (Figure 5).

Figure-5. Air relative humidity at the centre of the storage

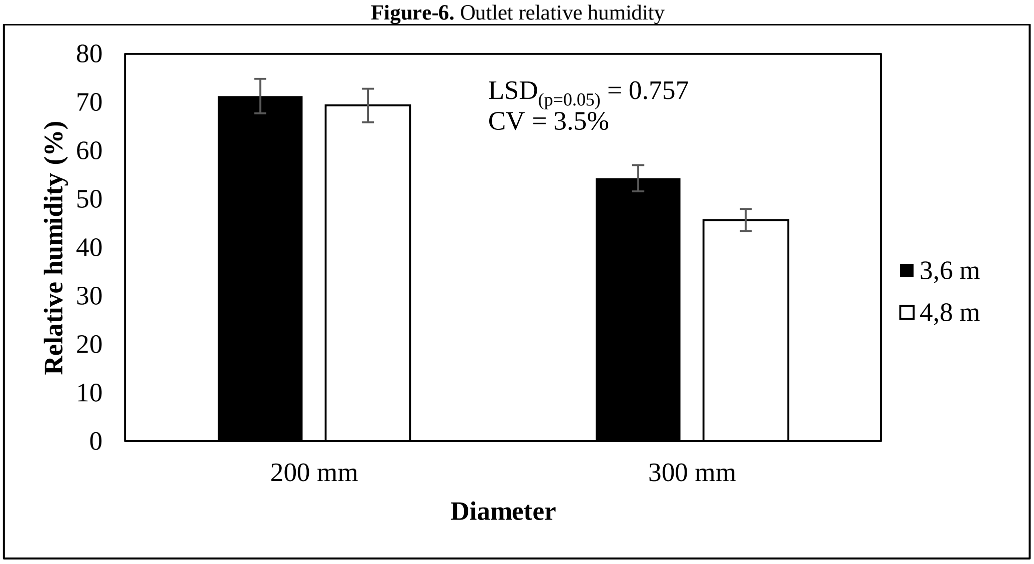


A chimney height of 4.8 m had a lower relative humidity than a chimney height of 3.6 m ($P \leq 0.05$). There was a significant difference between the combination of the diameter and height of the solar chimney ($P \leq 0.05$). The average relative humidity obtained in the room centre is higher than the relative humidity obtained in the inlets, due to the cooling of air, as it is drawn from the roof solar collector down to the centre of the room. The results showed that a 200 mm chimney diameter is not capable of extracting hot air from the roof solar collector, since there is no change in relative humidity in the centre, which is 70.9 ± 0.59% and 70.5 ± 3.35%, for 3.6 m and 4.8 m chimney heights, respectively, and which is relative to the initial relative humidity (69.7%). Both a diameter of 300 mm, and a height of 4.8 m had a significantly lower ($P \leq 0.05$) relative humidity (37.9 ± 0.47%) than a height of 3.6 m (44.6 ± 0.55%) (Figure 5). For a diameter of 300 mm, there was a larger decrease in relative humidity for both heights, relative to the initial relative humidity of 69.7%. To show that this 300 mm diameter chimney was working, the relative humidity was increased by 30.7% and 28.5%, for the 3.6 m and 4.8 m chimney heights, respectively. Increasing relative humidity implies that hot air is sinking in the storage space, from the inlets to the centre, which further implies circulation [41]. In the current study, the chimney size of 300 mm diameter and 4.8 m high gave better results, when compared to the other chimney sizes. Furthermore, there is a reduction in the relative humidity in the storage room.

3.4. Relative Humidity at the Outlet

The results show that the relative humidity at the outlet (71.3 ± 3.57% for 3.6 m) is similar to the relative humidity obtained at the centre of the storage room (70.9±0.59% for 3.6 m) for the for the same chimney diameter of 200 mm (Figure 6).

Figure-6. Outlet relative humidity

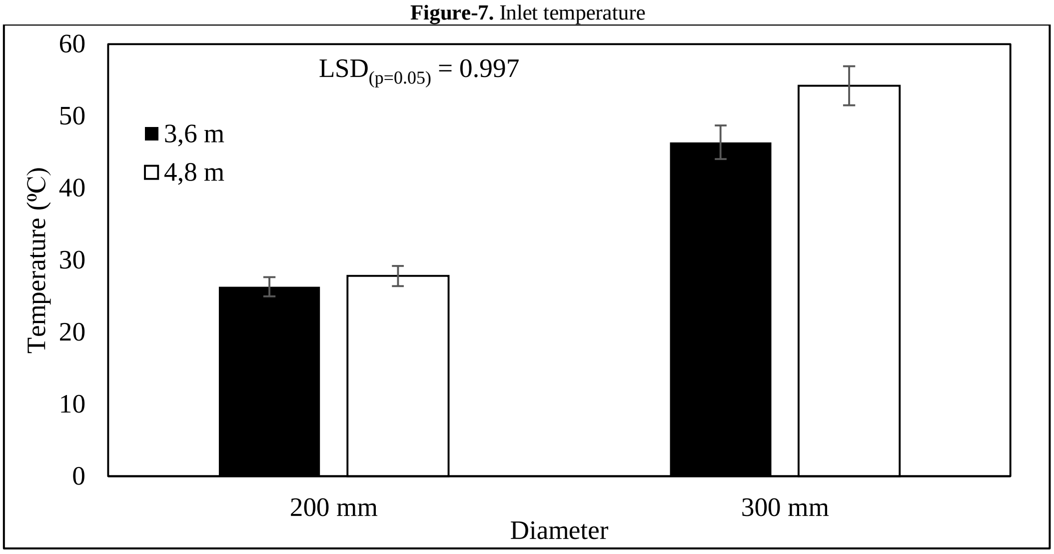


Similarly, for the height of 4.8 m, no change was observed. On the other hand, at a chimney diameter of 300 mm, a significant difference ($P \leq 0.05$) was observed between the relative humidity of air at the centre of the storage and the air at the outlet for both chimney heights. As the room space cools due to the downward movement of air, it retains a high relative humidity, which is the case with a chimney size of 300 mm. On the contrary, a chimney size of 200 mm shows no change in relative humidity, implying that there is no downward movement of the air. Relative humidity at the outlet for a chimney with a diameter of 200 mm is significantly higher ($P \leq 0.05$) than the relative humidity obtained for a chimney with a 300 mm diameter. For a 300 mm diameter chimney, lower relative humidity was achieved ($P \leq 0.05$) with 4.8 m high chimney (45.7 ± 0.53%), compared with a 3.6 m high chimney (54.3 ± 2.09%) (see Figure 6). Increasing the height and the diameter of the solar chimney improved its performance. A previous study by Ali [16] and Guo, *et al.* [40] obtained similar results. A chimney with a diameter of 300 mm and a height of 4.8 m performed better.

3.5. Temperature at the Inlet

A chimney with a diameter of 300 mm obtained high temperatures at the inlet, namely, 46.4 ± 4.87°C and 54.2 ± 2.64°C for both heights of 3.6 m and 4.8 m, respectively. On the other hand, a chimney with a diameter of 200 mm achieved low temperatures ($P \leq 0.05$) (Figure 7).

Figure-7. Inlet temperature

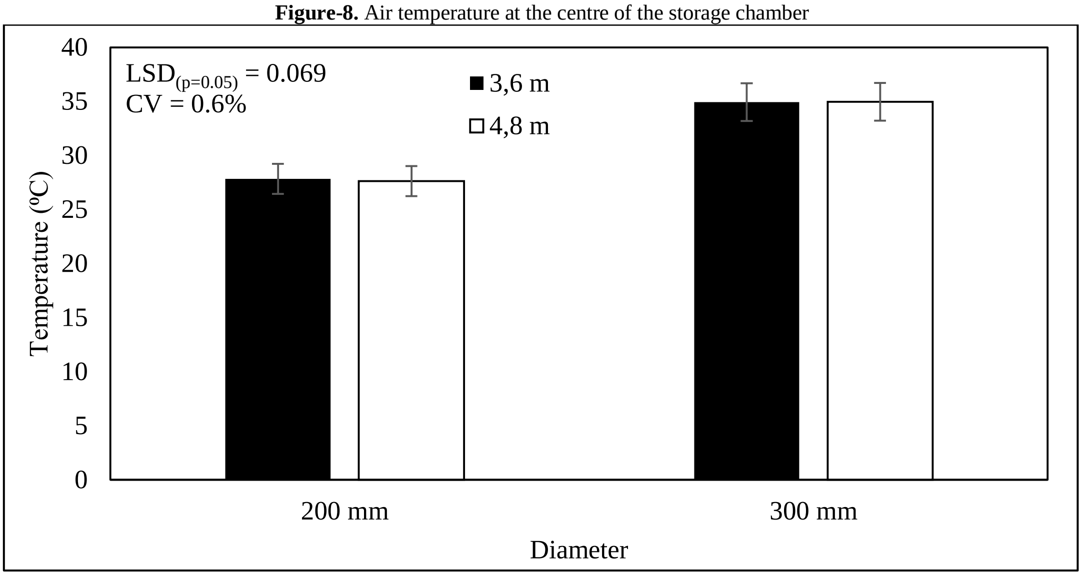


The inlet temperature increased by 23.1°C and 30.9°C, relative to the initial temperature in the storage room for a chimney diameter of 300 mm, and for heights of 3.6 m and 4.8 m. Temperatures in the roof solar collector were observed on the inlets when the chimney was in operation. High temperatures for the chimney with a 300 mm diameter were due to the chimney extracting hot air from the roof solar collector. For a chimney with a diameter of 200 mm, the temperature increases were smaller, i.e., 3°C and 4.3°C, for 3.6 m and 4.8 m chimney heights, respectively. These marginally small temperature increases were due to the pressure that developed in the solar collector during the heating of air [39], forcing the air into the inlets at irregular intervals. This causes a slight increase in the average temperature; however, if the 200 mm chimney developed adequate draft to extract hot air from the roof solar collector, the temperature increased significantly. This is evident from the temperature results produced by a chimney diameter of 300 mm, which had adequate suction power to extract hot air from the roof solar collector. Both the height and the diameter have an impact on the performance of the chimney. The 300 mm diameter chimney gave good results at a height of 4.8 m.

3.6. Temperature at the Centre

The centre temperature was significantly higher for the chimney with a diameter of 300 mm, compared to a diameter of 200 mm ($P \leq 0.05$). Figure 8 shows that for both chimney diameters of 200 mm and 300 mm, all the heights induced similar temperatures. The temperature decreased from 54.2 ± 2.64ºC at the inlet to 35.7 ± 0.15ºC at the centre (see Figure 8). A decrease in temperature indicates the movement of air as it enters the inlet from the roof solar collector down to the centre of the storage, where the seeds are stored. When the size of the chimney is increased, the movement of air is observed through the temperature profile at different locations in the storage space. This is particularly so for chimneys with a diameter of 300 mm, since a bigger chimney diameter has a smaller resistance flow coefficient, resulting in high airflow volume and more draft [42, 43]. However, the 300 mm chimney diameter, with the height of 4.8 m performed better than the rest of the chimney sizes.

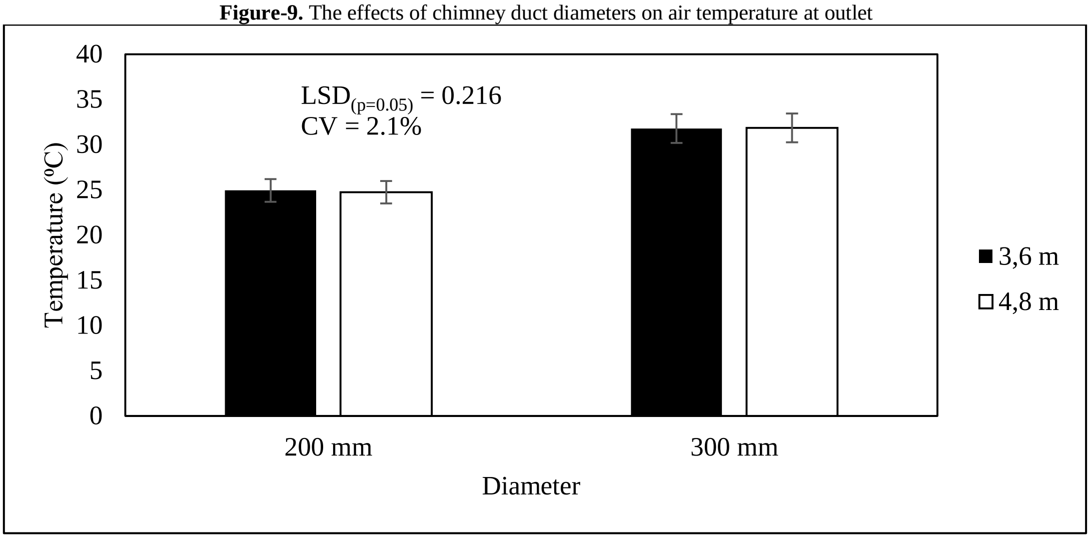
Figure-8. Air temperature at the centre of the storage chamber



3.7. Temperature at the Outlet

The temperature leaving the storage is measured at the chimney inlet (which is the room outlet) at the base. For a 300 mm diameter chimney, the temperature of the air at the outlet is lower than the temperature at the centre of the storage, since the outlet is at the bottom. The temperature decreased from 35.7 ± 0.15ºC at the centre to 31.8 ± 0.16ºC at the outlet (Figure 9).

Figure-9. The effects of chimney duct diameters on air temperature at outlet

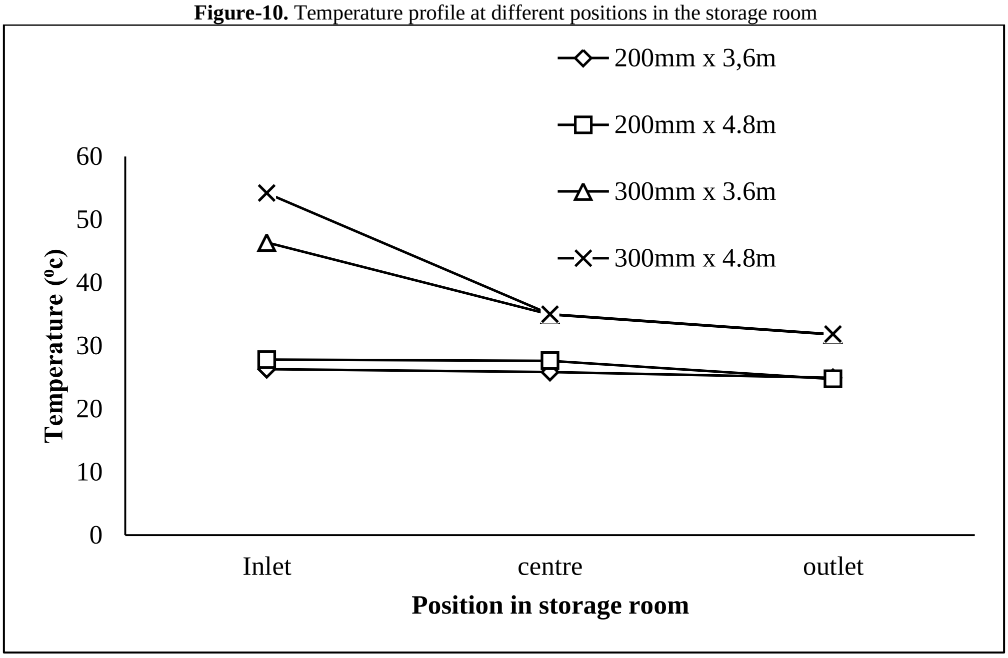


There is a significant difference between the results obtained for the different chimney sizes ($P \leq 0.05$). Larger chimney sizes performed better than smaller chimney sizes. It was found that the taller and bigger the chimney is, the better the results, and that a 300 mm diameter chimney, with the height of 4.8 m, had greater ventilation rate, when compared to the rest of the chimney sizes explored in this study. The temperature is lower at the outlet than in the other positions in the storage room, since the outlet is at the lowest point. Therefore, when hot air enters the inlets from the roof solar collector, it cools until it exits through the outlet at the bottom. Furthermore, the solar chimney provides suction when the air column inside the chimney body is heated [44-46]. In principle, hot air rises and the upward movement of air leaves a vacuum for the air beneath to fill, thus allowing a continuous flow of air in the chimney and the storage room [47]. The performance of the solar chimney is dependent on the size of the chimney; the higher the chimney, the better the results. Similarly, the larger the cross-sectional area the higher the ventilation rate [22, 48]. For the storage room under investigation, a chimney having a diameter of larger than 300 mm produces good results. It is similar to a chimney with a height of 3.6 m. However, increasing the diameter of the chimney further leads to a reverse flow, a case where air reverses its direction and moves back into the storage room, which is unwanted. The chimney, on the other hand, can be as high as it can be, although there is an optimum chimney height beyond which the draft no longer improves. This particular height was not achieved in the current study, which leaves an opportunity for conducting further investigations into this particular aspect.

3.8. Temperature and Relative Humidity Profile at Different Positions in the Storage Room

The air temperature at the inlet is high, and as air flows down towards the centre of the storage room the temperature decreases. This was observed for the chimney with a diameter of 300 mm for both heights (see Figure 10).

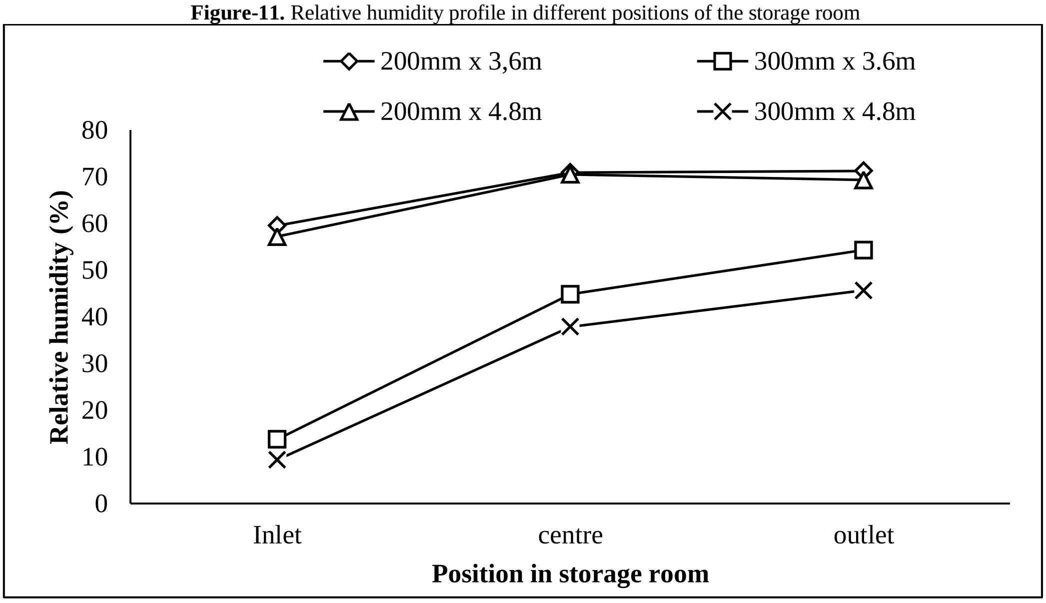
Figure-10. Temperature profile at different positions in the storage room



However, for a 200 mm diameter chimney, the temperature does not change, irrespective of the position in the storage room. In principle, the air cools as it sinks in space [31, 41], which implies that a chimney size with a diameter of 300 mm has an ability to circulate the air in the storage room and a chimney with a diameter of 200 mm does not induce air movement in a storage room.

The relative humidity for a chimney diameter of 300 mm for both heights (3.6 and 4.8 m) increases from the inlet, in the centre and at the outlet, which is attributed to the cooling of air as it moves down the space of the storage room (see Figure 11).

Figure-11. Relative humidity profile in different positions of the storage room



When the temperature decreases, the relative humidity tends to increase, since air with a low temperature has little capacity to hold moisture, resulting in high relative humidity [49-51]. On the other hand, the chimney diameter of 200 mm had a high relative humidity in all the positions in the storage room. This is an indication that the air is still in the storage space, when a chimney diameter of 200 mm is used.

4. Conclusions

The ventilation rates achieved by a chimney with a diameter of 300 mm and a height of 3.6 m and 4.8 m chimney heights were 3.4 $m^{3}\cdot m^{-1}$ and 6.4 $m^{3}\cdot m^{-1}$, which was greater than the minimum recommended ventilation rate for stored seeds [32]. Therefore, chimneys with a diameter of 300 mm and heights of 3.6 m and 4.8 m, meet the ventilation rate required for the storage of maize seeds. The ventilation rate was found to be significantly influenced by the effect of duct diameter than the height of the chimney. However, the optimum diameter was not reached in this study. It was found that a diameter of 300 mm was able to extract hot air from the solar collector and circulate it inside the storage space, but a diameter of 200 mm did not. The relative humidity increased from 9.4% to 45.7% at the outlet, from a height of 3 m at the inlets to the ground level at the outlet. Excessive cooling occurs when the air is circulated, and thus, the vertical distance between the inlets and outlets should be reduced, to keep relative humidity inside the storage as low as possible. The highest air temperature was recorded at the inlet while the lowest temperature was recorded at the outlet. The lowest relative humidity was recorded at the inlet while the highest air relative humidity was found to be at the outlet. The highest reduction in relative humidity was 60.3%, 31.8%, and 24%, at the inlet, centre and outlet, respectively, for a chimney size of 300 mm x 4.8 m. The chimney size with a diameter of 300 mm and a height of 4.8 m was able to lower the relative humidity in the storage room and a naturally-ventilated seed storage was developed. The storage facility can be tested under a wide range of external environmental conditions, to further observe its performance. It is, therefore, necessary to further explore the effects of chimneys that are larger than those used in the current study using Computational Fluid Dynamic models.

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