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Natural Convection Solar Tunnel Dryer for Maize: Design Process, CFD Simulation, Drying, Exergy and Economic Performance

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Abstract

This study explores the design, CFD simulation, experimental validation, exergy, and economic performance of a natural convection solar tunnel dryer for drying maize ears. The dryer, designed to address postharvest losses and promote sustainable drying practices, has a capacity of 114.2 kg and a total area of 5.0 m². It reduced the maize moisture content from 23.4% to 12.5% (wet basis) in 5 days, compared to 12 days under open sun drying. Experimental performance closely aligned with CFD simulations performed using SOLIDWORKS 2023, which predicted airflow and heat transfer.

The dryer effectively heated the air from an average of 25°C at the inlet to 55°C at the collector’s outlet end. The central and top sections exhibited the highest temperatures due to direct solar radiation, while slight cooling occurred near the outlet as heat was absorbed by the drying material and lost through convection and radiation. The chimney, designed as a vertical solar collector, enhanced airflow by increasing buoyancy pressure.

Exergy analysis identified losses due to irreversibility, suggesting chimney design modifications to improve airflow and exergy utilization. Economically, the dryer offered a payback period of 3.7 years, demonstrating its value in preventing postharvest losses and enhancing food safety.

This integrated approach highlights the feasibility and sustainability of natural convection solar dryers as effective solutions for postharvest maize drying, particularly in regions with similar climatic conditions.

Keywords: CFD simulation, economic performance, exergy, natural convection solar tunnel dryer, maize

1. Introduction

Maize and legumes are the main crops cultivated by small-holder farmers in Zambia, and in most of these farming communities, maize is the main source of nutrition. An estimated 70% of smallholder farmers directly depend on agriculture as their main source of income and food (Nzima, 2023), producing about 1.2 to 1.6 metric tonnes per hectare (Chiona, 2012). Maize has two growing seasons: the wet (rainy) summer season (November to April) when the smallholder farmers grow their maize and, the dry winter season (May to October) when most of the irrigated maize is grown (M’mboyi, Mugo, Mwimali, & Ambani, 2010). Due to inadequate drying facilities, small-scale farmers are compelled to harvest their maize well after it has reached physiological maturity. According to EIP-AGRI (2015), harvesting can be postponed for up to two months to give the maize time to dry. Delays in harvesting, invariably result in issues including the maize being vulnerable to termite, rodent and, domestic animal assaults, as well as insect infestation. According to Mukwangole and Simate (2017), maize has traditionally been dried by laying it on the ground, stoking with maize stalks, and placing over fire places. However, this process makes the crop vulnerable to weather-related factors (such as high relative humidity and rainy conditions) and theft. It also postpones field preparation in the event that a winter crop has to be planted. If the weather is very gloomy and humid, the crop will not dry out enough, which could lead to significant losses. Nzima (2023) reported that postharvest loss continues to be the biggest challenge facing the smallholder farmers, and this is despite their tremendous efforts to produce maize. The loses are estimated at 30% of the maize crop on a national average, thus strain efforts to increase the farmers' wellbeing and help them escape poverty. The World Food Program (2021) reported that postharvest losses affect 17% of smallholder farmers, with some households suffering losses of up to 50% of their output, and that lack of access to postharvest management and storage options are frequently the cause of this.

It is evident from the aforementioned reports that Zambia's smallholder agricultural systems rely heavily on maize, making postharvest issues crucial. Current practices are inefficient and contribute to significant losses, exacerbating poverty and food insecurity. Innovative solutions, such as improved solar drying technologies, could help mitigate these losses by providing efficient, weather-independent, and theft-proof drying mechanisms. Addressing these challenges would enhance productivity, reduce losses, and ultimately improve the well-being of smallholder farmers.

Solar dryers significantly reduce post-harvest losses of maize by using solar energy, thus offering advantages over other drying methods (Simate & Ahrné, 2006). They are classified according to the energy transfer mechanisms as direct mode (Chavan, Vitankar, Mujumdar & Thorat, 2020), indirect mode (Hussain, Ahmad, Ghafoor & Tanvir, 2020), and mixed mode (Andharia, Solanki, & Maiti, 2023). They are further classified based on airflow as forced (Salve & Fulambarkar, 2021) or natural convection (Simate, 2020). Natural convection solar dryers are cost-effective, require minimal electricity, and are ideal for rural areas (Shimpy, Kumar, and Kumar, 2023a; Rulazi, Marwa, Kichonge, and Kivevele, 2023). Studies highlight air temperature and flow rate as key performance factors (Chavan, Vitankar, Mujumdar, and Thorat, 2020), with innovations like chimneys (Hikmatov, Mavlonov, and Juraev, 2024) enhancing natural convection in these drying systems. It is therefore noted that solar dryers, especially natural convection types, provide a viable eco-friendly solution to reduce postharvest losses in maize and other crops. Innovations like mixed-mode designs and chimney-enhanced airflow further boost their efficiency.

Computational Fluid Dynamics (CFD) is useful in the study of complex fluid flow situations related to heat and mass transfer (Misha, Mat, Ruslan, Sopian, & Salleh, 2013), thus helping in improving solar dryer designs by providing accurate predictions of airflow and temperature distribution (Román-Roldán, Yudonago, López-Ortiz, Rodríguez-Ramírez, & Sandoval-Torres, 2021). Since physical experiments are not used, the cost and difficulty related to the estimation of air velocity and temperature in the drying chamber are avoided (Natarajan & Elavarasan, 2019). CFD simulation of a natural convection solar tunnel dryer done by Mukanema and Simate (2023) indicated that heat was lost through the chimney, that air was recirculated in the collector, that pressure was lost in the airflow throughout its passage from the drying chamber to the chimney, and that there was a partial decrease in velocity in certain areas of the dryer. Abdi and Ahmad (2022) used a two-dimensional model of a mixed-mode solar dryer to perform numerical simulations of unsteady laminar airflow and heat transfer using CFD analysis. The single cabinet dryer's many parts were able to maintain the necessary consistent temperature distribution according to the suggested design layout. From the foregoing literature, it is noted that CFD provides a detailed and cost-effective way to study and optimize the internal dynamics of solar dryers. Insights like those from Abdi and Ahmad (2022) enable targeted improvements in airflow, temperature distribution, and overall dryer efficiency. Addressing the identified issues such as heat loss, air recirculation, and pressure drop can significantly enhance the performance of natural convection solar dryers and contribute to more sustainable and effective drying solutions.

Exergy analysis is useful in offering the best answers to drying problems, despite the challenges in understanding the drying processes that are highly dependent on temperature and moisture content (Dincer & Rosen, 2007). The exergy efficiency of solar drying systems is often employed as a sustainability indicator because it illustrates how much energy is required in the process (Akpinar, 2018). According to Kumar, Ranjan, Prakash, and Shukla, (2017), research activities on the energy of various solar dryer types have been conducted to reduce losses so that resources would be used as efficiently as possible, resulting in financial gains. They concluded that exergy analysis provided a more accurate performance assessment of the solar dryer system and that significant data on operations, losses and causes of failure, could be acquired. Boulemtafes-Boukadoum and Benzaoui (2011) conducted an energy and exergy analysis of the mint drying process using an indirect natural convection solar dryer and were able to estimate the energy supplied for drying as well as the exergy loss. Ultimately, drying processes are complex and depend on factors such as temperature and moisture content. Exergy analysis provides insights into these dynamics, offering solutions to optimise drying operations. Exergy efficiency reflects how effectively energy is utilised in the drying process. This efficiency serves as an indicator of the sustainability of solar drying systems. Exergy analysis enables a deeper understanding of system operations compared to energy analysis alone. It identifies operational losses and their root causes, which can guide improvements in design and operation. Studies (e.g., Kumar, Ranjan, Prakash, and Shukla, 2017) highlight its role in minimising energy losses, leading to more efficient resource use and financial savings.

The payback period is one of the economic analyses that are done to determine if a project should be adopted (Aymen, Hamdi, Kooli, & Guizani, 2019). The goal of a solar dryer's economic evaluation is typically to ascertain its payback time (Banout, Havlik, Lojka, Polesny, & Verner, 2011). Borkakoti, Das, and Gupta (2024) dried ginger and turmeric in a solar greenhouse dryer and found that the dryer's payback period was affected by the buying and selling price of the dried product. Compared to the 20 years of operation of the dryer, the short payback periods of 0.55 years for ginger and 0.81 years for turmeric were insignificant, which made the dryer run with minimum expenditures. They concluded that the greenhouse dryer was viable and could be deployed. Ultimately, the payback period serves as a vital indicator of the economic success of solar dryers. A short payback period increases the attractiveness of solar dryers to farmers and entrepreneurs by highlighting quicker returns on investment. By addressing factors such as product pricing and operational efficiency, it is possible to make solar drying systems more financially accessible and appealing, fostering widespread adoption in both rural and commercial settings.

Although various studies have been conducted on different aspects of solar dryers, such as design, drying performance, exergy, CFD simulation, and economic analysis, studies combining all these aspects on solar tunnel dryers for maize ears are lacking. This has led to a dearth of thorough data that facilitates well-informed decision-making, enabling designers, manufacturers, and future consumers to make better decisions based on a balanced comprehension of technical performance and economic ramifications. Thus, the goal of the current work was to design and build a natural convection solar tunnel dryer for maize ears, simulate it using CFD, carry out experiments, and conduct exergy and economic analysis. The dryer was designed to hold 114.2 kg of physiologically mature maize ears with a moisture content of 23.4% wet basis, which would yield 100 kg of dried maize at a moisture content of 12.5% wet basis. The dryer's temperature fluctuations were depicted, and airflow and heat transfer were simulated using CFD. Significant losses were found via exergy analysis, which also recommended areas for improvement. The payback period of 3.7 years was determined by the economic study. By integrating these aspects, a comprehensive understanding of the dryer's performance can be achieved. The design process ensures the system meets functional requirements, while CFD simulations provide precise airflow and temperature predictions, and exergy analysis identifies energy losses. Economic performance evaluation ties it all together, ensuring practicality and feasibility.

2. Methodology

The sample selected for this study was the Seed Co SC513 maize hybrid seed. It matures early and is ready for drying in April when the wet rainy season comes to an end. The absence of rain during this time presents a favourable environment for the solar drying of the maize. The solar drying equipment was chosen because of its straightforward design, ease of construction by a local carpenter, affordability for rural residents, and utilisation of locally accessible resources. CFD was used to model airflow and heat transfer and show temperature variations throughout the dryer. Further, it would confirm the effective operation of natural convection principles. This is important as it can reveal areas of the dryer that may need some adjustments in order to improve the performance. Exergy analysis is useful in highlighting significant losses arising from irreversibility and pointing out areas of potential improvements. Through exergy, the rate of heat consumed in evaporating moisture from the maize ears could be determined, thus making it possible to come up with the size of the collector and drying area.

2.1 Design Process

It was required to produce 100 kg of dried maize ears with a safe storage final moisture content (FMC) of 12.5% wet basis. The maize to be dried had reached physiological maturity, and its initial moisture content (IMC) was 23.4% wet basis. For the drying equipment, a natural convection solar tunnel dryer was selected to be used to dry the maize ears and consequently designed and fabricated. Using equation (1), the initial mass (IM) of physiologically mature maize ears was estimated from the final mass (FM) that the maize ears would attain at the end of the drying process.

$$IM = \frac{FM(1-FMC)}{(1-IMC)} \tag{1}$$

The initial mass was determined to be 114.2 kg. Therefore, the amount of water Mw to be evaporated from the maize ears was 14.2 kg, resulting in a final mass of 100 kg.

The maize ears' loading density (LD) was ascertained. It measures the quantity of product loaded per unit tray area and therefore helps determine the appropriate size for the dryer's drying area. The loading density was determined from the mass of fresh maize ears (MFME) and the drying area (DA) using a method given by Leon, Kumar and Bhattacharya (2002), as

$$LD = \frac{MFME}{DA} \tag{2}$$

The loading density was determined by taking a sample of 15 randomly picked physiological mature maize ears that had attained a moisture content of 23.4% wet basis and had their covers removed. The maize ears were put side by side on a flat surface without piling them on top of each other. Then the maize ears' total weight and the surface area they covered were noted as 4.56 kg and 0.18 m^2, respectively. The loading density was then calculated using equation (2), giving a value of 24.7 kg/m^2. The area of the drying tray that could accommodate the initial mass was then determined. This was obtained from the product of the initial mass and the loading density, giving a value of 4.63 m^2, which was rounded off to 5.0 m^2.

To determine the solar collector area, the approach used in previous studies (Schirmer, Janjai, Esper, Smitabhindu, & Mühlbauer, 1996; Bala, Mondol, Biswas, Chowdury, & Janjai, 2003; Hossain & Bala, 2007) was used, where the collector area was made equal to the drying area. Therefore, this implies that the total area of the dryer that received solar radiation was 10 m^2.

The theoretical performance of the designed dryer in terms of the number of days required to reduce the moisture content from 23.4% to 12.5% was estimated. The amount of water to be removed from the maize ears to reduce its mass from 114.2 kg with 23.4% moisture content to the final mass of 100 kg with 12.5% moisture content is 14.2 kg.

The total energy (Q_T) required for drying, as described in Equation 3, comprises the sensible heat needed to raise the temperature of the maize ears, with an average mass of 114.2 kg, from ambient temperature to the evaporation temperature, and the latent heat required to evaporate 14.2 kg of water from the maize ears, assuming that drying occurs at 60°C. The drying is considered to be done for a number of days N_d, and on each day of drying, the maize ears are heated from ambient temperature to 60°C, the temperature at which evaporation of moisture occurs. Q_T was estimated using equation (3), where M_w is the mass of water evaporated, kg; h_{fg} is the latent heat of vaporisation, J/kg; M_{av} is the average mass of maize ears (average of initial and final mass), kg; T_d is the temperature of the dryer at which moisture evaporation takes place, °C; and T_{am} is the ambient temperature, °C.

$$Q_T = M_w h_{fg} + M_{av} C_p (T_d - T_{am}) N_d \tag{3}$$

The total area (collector and drying tray) A_T in m^2, for collecting solar energy in the solar tunnel dryer based on the number of days required to dry the maize ears is given by equation (4) (Janjai and Keawprasert (2006)), where η is the drying efficiency, %; and R is the monthly average daily solar radiation on a horizontal surface, W/m^2-day.

$$A_T = \frac{Q_T}{\eta R N_d} \tag{4}$$

From equations (3) and (4), the equation for determining the number of days N_d required to dry the maize is developed and is given by equation (5).

$$N_d = \frac{M_w h_{fg}}{\left(A_T \eta R - C_p M_{av} (T_d - T_{am})\right)} \tag{5}$$

The solar radiation, *R*, was taken as the average for April, May, and June, when the maize reaches physiological maturity and when the drying is done.

Having determined the total area (A_T) of the dryer, the major components of the dryer, i.e., the solar collector, the drying chamber, and the flat-plate solar chimney, were determined. The length and width of the dryer were 5 m and 2 m, respectively. Plywood boards were used to make the collector absorber plate, drying chamber floor, and all the sides of the dryer. To boost the absorptivity of solar insolation, the collector absorber plate was painted matte black. UV-stabilised greenhouse plastic was used to cover both the collector and the drying unit. It was intended for the airflow to pass over the solar collector's absorber. According to Brenndorfer (1985) and Ekechukwu and Norton (1999), this kind of solar collector has little heat loss.

A one-metre vertical solar chimney consisting of a covered flat plate collector was mounted to the drying unit's end to enhance airflow in the dryer. The chimney was constructed from plywood boards, and for better solar radiation absorption, a flat sheet of black-painted galvanised iron was placed on the entire front portion of the chimney and covered with UV-stabilised greenhouse plastic. The parameters used in the design of the dryer are given in Table 1, while the collector, drying unit, and chimney setup are shown in Figure 1.

Table 1. Parameters used in the design of the dryer

Parameter	Value	Units	Source
Loading Density, LD	24.7	kg/m^2	Measured, as used by Leon, Kumar and Bhattacharya (2002)
Total Area, A_T	10	m^2	Calculation
Monthly Average Daily Solar Radiation, R	17.8	W/m^2-day	https://weather-and-climate.com/average-monthly-hours-Sunshine.Lusaka.Zambia
Drying efficiency, η	10.8	%	Schiavone (2011)
Initial Moisture Content	23.4	% w.b.	Experiment
Final Moisture Content	12.5	% w.b.	Experiment
Number of Drying days, N_d	5.3		Calculation

Figure 1. Natural Convection Solar Tunnel Dryer

The operation of the solar dryer is such that convective heat transfer occurs at the cover and absorber plate of the collector unit as a result of solar energy passing through the transparent cover. This heats the air entering the collector unit through the bottom front end of the collector, reducing its relative humidity. The air in the collector unit is forced into the drying unit due to buoyancy pressure, which is created when the heated air becomes less dense than the surrounding air. At the drying unit, mass and heat transfer between the product and the air takes place, and hence the air temperature reduces while the relative humidity increases due to moisture transfer from the product to the air. Through the chimney unit, the air exiting the drying unit is further heated and rises by natural convection and exits the dryer through the rear top of the chimney, and the process continues as long as there is solar radiation (Al-Neama & Farkas, 2016; Seetapong, Chulok, & Khoonphunnarai, 2017).

2.2 Experimentation

The Department of Agricultural Engineering field station at the University of Zambia served as the site for the drying test. The location's coordinates are longitude 28.3°E and latitude 15.3°S. Before the experiment, the dryer was positioned so that the front side of the chimney faced north and its length was aligned with the north and south. After determining the moisture content of the maize in advance, 114.2 kg of maize ears with their covers removed were loaded into the dryer (Figure 2), and the drying experiment was started. The drying was carried out daily from 9:00 to 16:00 hours until a moisture content of 12.5% was reached.

Figure 2. Maize on ears loaded in the solar tunnel dryer

The solar dryer was equipped with a multi-probe Campbell Scientific Inc. data logger (CR 1000) to record the air temperature using thermocouple-style temperature probes (model: T108, accuracy ±0.2 °C, range -5 to +95 °C), relative humidity using a combined temperature and relative humidity probe (model: HMP60-L), and solar radiation using a pyranometer (Kipp and Zonen, Model CM11, accuracy ±0.5 W/m^2). For air velocities between 0 and 30 m/s, a digital airflow meter (Model TES 1340, precision 0.1 m/s) was utilised for the measurements.

Figure 3. Collector air temperature measurement

Figure 4. Drying chamber air temperature measurement

Figure 5. Chimney air temperature measurement

For sun drying, a sample of maize ears was put on a plastic sheet as shown in Figure 6.

Figure 6. Open Sun Drying

2.3 Exergy Analysis

The exergy content of the heat transfer ($Ex_{ideal\text{-}gas}$) is described by the energy exchanged, the boundary temperature (T), the temperature of the atmospheric reservoir (T_o), the boundary pressure (P), and the atmospheric pressure (P_o), resulting in Equation (6) as the flow exergy of an ideal gas (Bejan, 2016).

$$Ex_{ideal-gas} = C_p\left(T - T_0 - T_0 ln\left(\frac{T}{T_0}\right)\right) + RT ln\left(\frac{P}{P_0}\right) \tag{6}$$

There are two sources of exergy for the energy input into the drying chamber: the heated air from the collector and the direct solar radiation that the drying chamber receives (Jafarkazemi & Ahmadifard, 2013). Equation (6) is modified after assuming that the change in pressure between the inlet and outlet of the solar dryer is insignificant and taking into consideration the mass airflow. The result is Equation (7), which gives the exergy of air exiting the collector and entering the drying chamber ($Ex_{air\_in\_dch}$).

$$Ex_{air\_in\_dch} = M_a C_p\left[T_{in\_dch} - T_{amb} - T_{amb} ln\left(\frac{T_{in\_dch}}{T_{am}}\right)\right] \tag{7}$$

For the inlet exergy into the drying chamber due to solar radiation ($Ex_{solar\_in\_dch}$), Equation (8) is used:

$$Ex_{solar\_in\_dch} = A_{dch} I_{solar}\left[1 - \left(\frac{T_{amb}}{T_{solar}}\right)\right] \tag{8}$$

Where:

M_a: Mass flowrate of air, kg/s

C_p: Specific heat capacity of air, J/kg K

$T_{in\text{-}dch}$: Temperature of air entering drying chamber, K

T_{amb}: Ambient temperature, K

T_{solar}: Temperature of the sun, K (a value of 5,500 K from NASA (2022) is used)

A_{dch}: Area of the drying chamber, m^2

I_{solar}: Solar radiation, W/m^2

Further, at the air exit of the drying chamber, the exergy of air ($Ex_{air\_out\_dch}$) can be determined based on its temperature (T_{out_dch}) and that of the ambient, as given by Equation (9).

$$Ex_{air\_out\_dch} = M_a C_p \left[T_{out\_dch} - T_{amb} - T_{amb} ln\left(\frac{T_{out\_dch}}{T_{amb}}\right)\right] \tag{9}$$

Equation (10) shows that the total exergy entering the drying chamber is equal to the total of the various exergies within the drying chamber, i.e., due to the product, the waste, and the destruction (Dincer & Rosen, 2007).

$$Ex_{in-dch} = Ex_{product} + Ex_{waste} + Ex_{destruction} \tag{10}$$

The exergy released with trash to the outside of the dryer (Ex_{waste}) and the exergy destroyed inside the drying chamber due to internal irreversibility ($Ex_{destruction}$) together constitute the exergy loss (Ex_{loss}) in the drying chamber.

Equation (11) determines the exergy output in the product ($Ex_{product}$) for a natural convection solar dryer, which is the rate of heat consumed in evaporating moisture from the maize ears (Kumar, Ranjan, Prakash, and Shukla, (2017)).

$$Ex_{product} = Q_{evap}\left[1 - \left(\frac{T_{am}}{T_{maize\_ears}}\right)\right] \tag{11}$$

Where:

Q_{evap}: Heat used for evaporation of moisture from the maize ears, J/s, and is given by equation (12)

m_{evap}: Rate of moisture evaporation, kg/s

h_{fg}: Latent heat of vaporisation, J/kg, evaluated at T_{maize_ears}, the temperature of the maize ears, K.

$$\mathrm{Q_{evap} = m_{evap} h_{fg}} \tag{12}$$

2.4 CFD Analysis

The geometric model of the solar tunnel dryer under study was designed in 3D using SOLIDWORKS 2023, as shown in figure 7. The simulation was performed using the CFD software SOLIDWORKS 2023 FLOW SIMULATION. The developed numerical model for CFD analysis was carried out in a steady state. Flow and transport phenomena for airflow and heat transfer are described by the Navier-Stokes equations. The Navier-Stokes equations are a mathematical formulation of the flow of incompressible or compressible fluid for the momentum, mass, and energy, given by Matsson (2023) as:

Mass conservation equation

$$\nabla(\rho U) = 0 \tag{13}$$

Momentum conservation equation

$$\nabla(\rho UU) = \nabla p + \mu T \nabla U^2 + \rho g + S_h \tag{14}$$

Energy conservation equation

$$\nabla(-kT + \rho C_p T U) = 0 \tag{15}$$

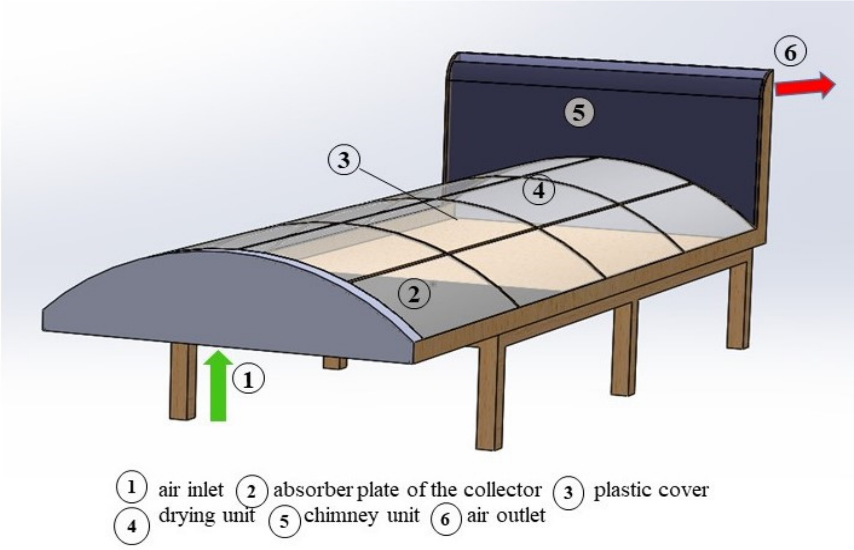

Figure 7. Geometric model of the natural convection solar tunnel dryer

2.5 Economic Analysis

The economic analysis is based on the monetary equivalent of maize that could have been lost due to postharvest losses but has been preserved by the solar dryer. The losses experienced when maize is left to dry in the field include shatter losses arising from handling during the harvesting process and losses arising from maize getting soaked by late rains. It should be noted that when maize is left in the field to dry, the land occupied by the maize cannot be used for other farming activities, thus denying the farmer an opportunity to earn some income from another crop. It is further noted that when maize is soaked in the field by late rains, there is a high risk of aflatoxins developing on the maize, making it unsuitable for human consumption.

To ascertain how long it might take a farmer to repay the loan for the solar dryer, the payback method is employed in this analysis. The monetary equivalent of the 30% postharvest losses is used annually to pay towards the loan to purchase the solar dryer, and it is assumed that the farmer would not suffer these losses when the maize is dried in the solar dryer.

The Payback Period (*PBP*) in years is given by Sreekumar, Manikantan and Vijayakumar (2008) as,

$$PBP = \frac{ln\left[1-\frac{CC}{SV_1}(Int-Inf)\right]}{ln\left(\frac{1+Inf}{1+Int}\right)} \tag{16}$$

Where:

CC: Capital cost, comprising of the materials and labour to build the dryer, ZMW

SV_1: Savings during the first year of operation, ZMW

Inf: Rate of inflation, %

Int: Rate of interest, %

The rate of inflation and the rate of interest were taken as 13.2% and 26.2%, respectively (Trading Economics, 2024). The Capital Cost (CC) includes the materials and labour required to construct the dryer and is presented in Table 2. The main material for the tunnel and chimney of the dryer is plywood. Plywood is resistant to cracking, splitting, and warping, making it suitable for many external applications. According to Vinawoodltd (2024), plywood can last for 20 to 30 years in outdoor applications. For the current study, however, a lifespan of 10 years is used. To support the dryer, a stand made of timber was used.

Table 2. Materials for building the dyer

No.	Material	Units	Quantity	Unit cost, ZMW	% of Capital	Total cost, ZMW
1	Plywood (2.44m*1.22m*18mm)	pieces	4	900	54.0	3600.00
2	Timber (50mm*50mm*5m)	pieces	10	110	16.5	1100.00
3	Galvanized Iron sheet (2m*0.9m*0.3mm)	pieces	1	210	3.1	210.00
4	Plastic Net for tray	m^2	2.5	145	5.4	362.50
5	Black paint (gloss)	litres	1	100	1.5	100.00
6	4-inch Wire nails	kg	1	40	0.6	40.00
7	Industrial stapples	kg	1	150	2.2	150.00
8	Wood glue	litres	0.5	70	0.5	35.00
9	Greenhouse Plastic	m^2	18	32.4	8.7	583.20
10	Total Materials				92.7	6180.70
11	Labour to build dryer (10%) of total materials					618.07
12	Capital Cost (materials to build + labour)					6,798.77

The savings during the first year of operation were determined as follows: The mass of dried maize ears produced each week (5 days of drying per week) is 100 kg, which, when shelled, yields 85.4 kg of dried maize grain. Over 12 weeks (four weeks each in April, May, and June, when drying is conducted), the total dried maize grain produced is 12 * 85.4 kg = 1,024.8 kg. The Food Reserve Agency, the country's national food storage organization, purchases dried maize at ZMW 6.60/kg. Therefore, the total revenue from the sale of dried maize is 1,024.8 kg * ZMW 6.60/kg = ZMW 6,763.68. Considering the 30% of the maize yield that could have been lost if the maize was left to dry in the field, the savings after one year amount to 30% * 1,024.8 kg * ZMW 6.60/kg = ZMW 2,029.10. These revenue and savings figures are then incorporated into the economic performance analysis presented in Table 3.

3. Results and Discussion

3.1 Drying Performance

The mechanisms through which the dryer influences drying performance are determined by the design and operation of the dryer. The transparent cover of the dryer allows solar radiation to heat the drying chamber and the collected air, raising the temperature and facilitating moisture evaporation from the maize ears. As the air inside the dryer heats up, it becomes less dense and rises, creating a natural upward flow through the chimney. This movement draws cooler, ambient air into the system through the air inlet, allowing air to be heated as it passes through the collector and maintaining a continuous flow across the drying materials. The chimney accelerates air movement by increasing buoyancy pressure, which improves the removal of humid air from the drying chamber. Faster removal of moist air reduces the relative humidity in the chamber, speeding up the drying process. The design of the dryer and chimney ensures a steady flow of warm air across the maize ears, leading to uniform heat distribution and consistent drying. CFD-optimised designs can further enhance this distribution by reducing recirculation zones and pressure losses.

Figure 8 illustrates the air temperature at various sections of the solar dryer and in the ambient environment at different times of the day during the five-day solar drying experiments. The temperatures fluctuated throughout the day, following the solar radiation pattern, which averaged 568.6 W/m². This pattern is consistent with findings from previous research by Mukanema and Simate (2024) on a natural convection solar tunnel dryer for bananas. In the current study, the average temperatures recorded were 26.2°C for the ambient air, 44.1°C for the solar collector, 44.4°C for the drying chamber, and 34.8°C for the chimney. The chimney temperature was 8.6°C higher than the ambient temperature, demonstrating its effectiveness in creating buoyancy to facilitate airflow within the dryer.

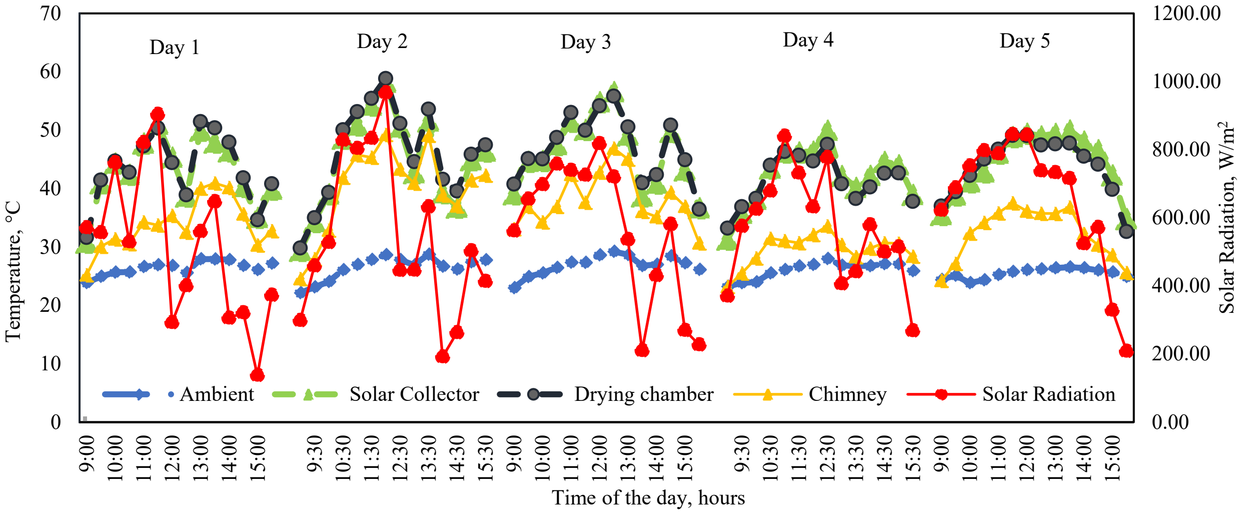

Figure 8. Temperature of air at various sections of the solar dryer and in the ambient at different times of the day

Figure 9 illustrates the variation in relative humidity within the solar collector and the ambient environment. Similar to the temperature graph, the relative humidity fluctuated in response to solar radiation but inversely to air temperature. As air temperature increased, relative humidity decreased, allowing the air to carry more moisture from the drying maize ears. This highlights the crucial role of the solar collector in the solar dryer, that of heating the ambient air and lowering its humidity, thereby enhancing its moisture-carrying capacity.

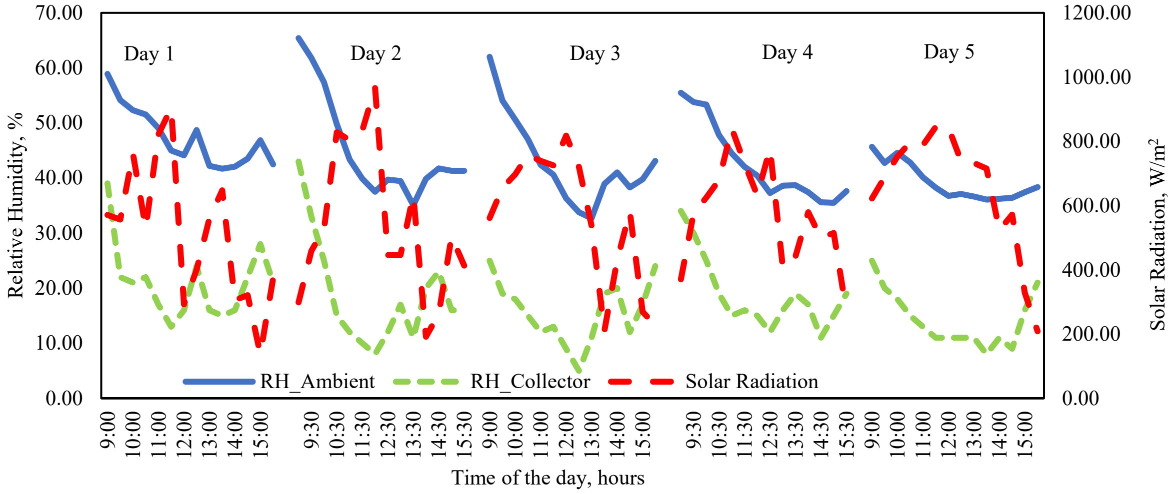

Figure 9. Relative Humidity in the ambient and solar collector at different times

Figure 10 shows airflow at different times of the day. The airflow depends on the difference between the air temperature inside the chimney and that in the ambient, thus fluctuations in the air temperature are reflected in the airflow. The airflow ranged from 0.00278 to 0.07506 kg/s with an average airflow of 0.0334 kg/s. These values are within the range found by other researchers on natural convection solar dryers, i.e., Berinyuy, Tangka and Weka Fotso (2012), 9.68 m^3/h, which is equivalent to 0.0029 kg/s; Bala and Woods (1994), 0.006 to 0.1 kg/s; Othieno (1987), 0.05 to 0.3 m/s equivalent to 0.0021 to 0.0123 kg/s; and Simate (2020), 0.00132 to 0.0088 kg/s.

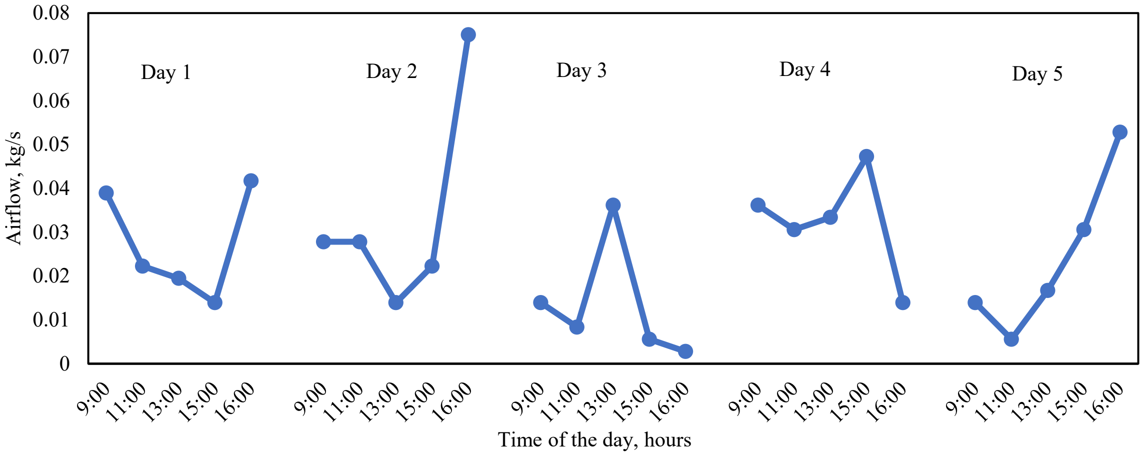

Figure 10. Airflow through the dryer at selected times of the day

Figure 11 illustrates the changes in moisture content of maize ears dried in the solar dryer and under open sun drying. Using the solar dryer, it took 5 days to reduce the moisture content from 23.4% (wet basis) to the safe storage level of 12.5% (wet basis), compared to 12 days for open sun drying. The higher average temperature in the solar dryer (42.3°C) facilitated faster moisture evaporation, whereas open sun drying had a lower average temperature of 26.0°C. It is also noted that our design calculations estimated a drying time of 5.3 days, demonstrating the accuracy and reliability of the design process.

Hamed and Reza (2014) observed that drying time for lemon was 17– 45% shorter with solar drying compared to sun drying, and that the solar-dried fruit retained a brighter colour. Hussain, Ahmad, Ghafoor, and Tanvir (2020) dried 100 kg of maize in a forced convection solar dryer under ambient temperatures of 28.5–35.3°C, solar radiation levels of 680–840 W/m², and relative humidity values of 71– 43%. Their system dried maize from an initial moisture content of 24% to a safe moisture content of 14% in 4 days, while open sun drying required 9 days.

These findings confirm that the performance of our natural convection solar dryer aligns well with results from previous studies, underscoring its efficiency and effectiveness for maize drying.

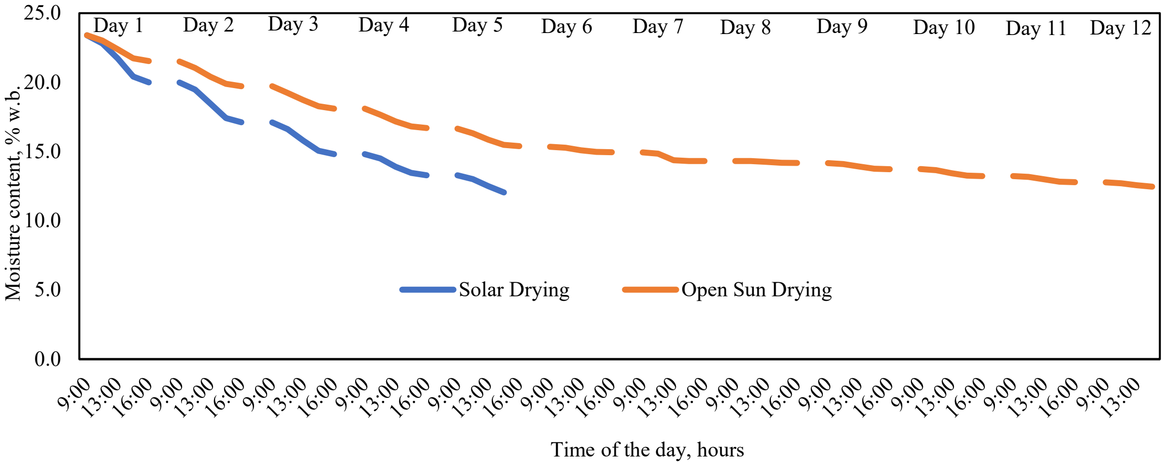

Figure 11. Moisture content changes with time of the day

3.2 Exergy Performance

The exergy of solar radiation and the exergy of hot air entering the drying chamber are shown in Figure 12. The exergy of solar radiation typically follows the variation in solar radiation, with maximum values occurring around noon, ranging from 652.8 to 4,582.7 J/s. The air entering the drying chamber is preheated by solar radiation in the solar collector, resulting in its exergy also peaking around midday. The exergy of the heated air ranges from 0.5 to 46.6 J/s.

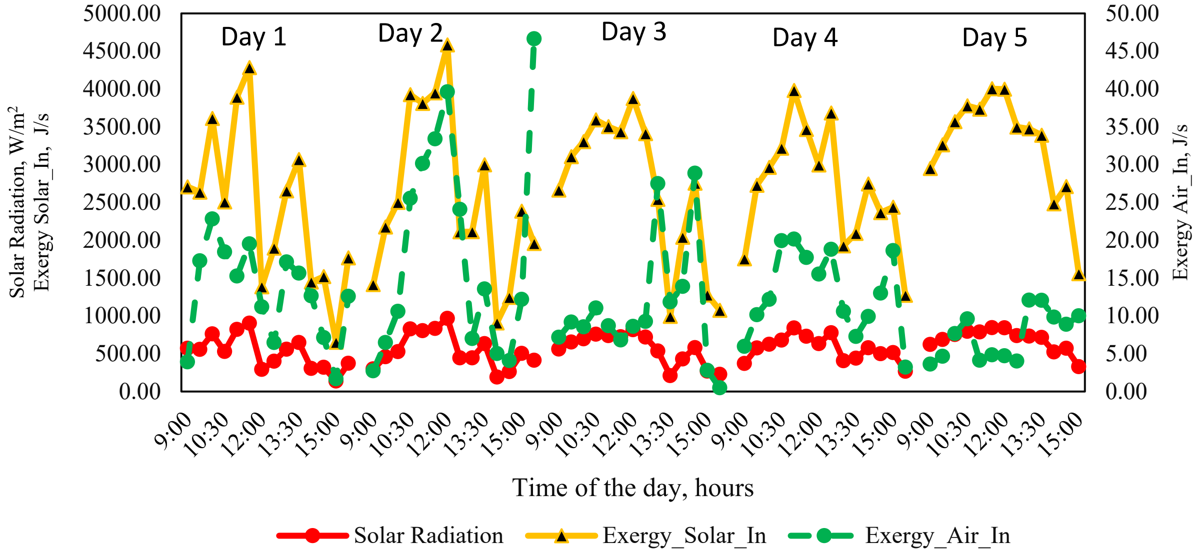

Figure 12. Exergy of Solar Radiation and Hot Air entering the Drying Chamber

Figure 13 shows the total exergy entering the drying chamber, the exergy used for moisture evaporation from the maize ears, and the exergy lost. The exergy of evaporation ranges from 0 to 40.6 J/s, while the exergy entering and exergy loss range from 654.5 to 4,622.3 J/s and 640.5 to 4,586.0 J/s, respectively. The exergy loss is significantly higher than the exergy of evaporation, indicating poor utilization of the exergy entering the drying chamber. Subramani, Dana, Natesan, and Leo (2020), in their study on greenhouse drying of turkey berries and ivy gourds, also observed that energy efficiency was higher than exergy efficiency, attributing this to energy losses caused by irreversibility. Hatami, Payganeh, and Mehroenahi (2020) suggested that irreversibility can be reduced with increased airflow.

In our study, airflow is driven by buoyancy created in the chimney due to the temperature difference between the chimney interior and the ambient environment, as well as the chimney height. Increasing the chimney height would likely improve airflow, thereby enhancing the exergy of evaporation. A higher exergy of evaporation would result in an increased drying rate, improving the dryer's efficiency and economic viability.

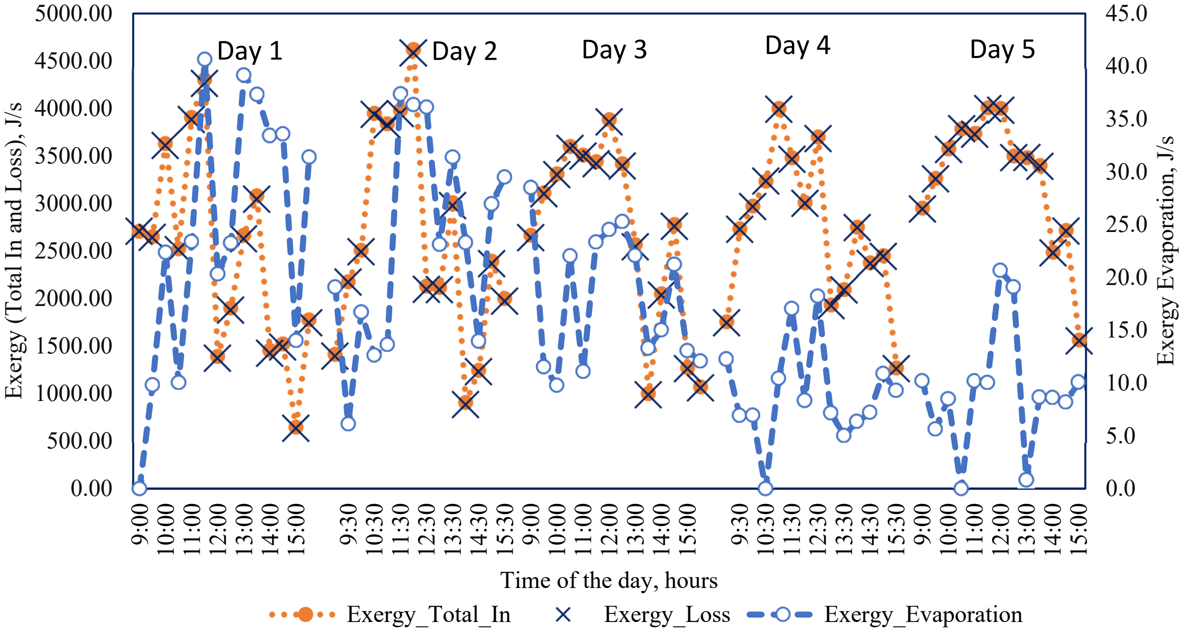

Figure 13. Drying Chamber Exergy, Total In, Loss and Evaporation

3.3 CFD Simulation

At the air inlet of the collector, the air was relatively cooler, with an average temperature of 25°C, as it had not yet undergone significant heating. As the air moved through the dryer, it was progressively heated, reaching an average temperature of 55°C at the end of the collector unit. Due to the mixed-mode design of the dryer, the centre and top sections of the tunnel typically exhibited the highest temperatures, further increased by solar radiation, as shown in Figures 8(a) and 8(b). Mukanema and Simate (2023) similarly observed that air temperatures increased as the air passed through the drying unit, primarily due to direct solar radiation heating the drying chamber.

Figures 8(a) and 8(b) also reveal spatial temperature variations within the dryer. Near the outlet, the air cooled slightly as heat was absorbed by the drying material and dissipated through convective and radiative processes, though the temperature remained generally higher than at the inlet. The chimney was designed and operated as a vertical flat-plate solar collector with a greenhouse plastic cover serving as glazing. This design enabled the chimney to heat the air from the drying chamber, enhancing buoyancy pressure and thereby contributing to improved airflow.

Airflow in the dryer was driven by buoyancy-induced natural convection and flowed through the system at an average velocity of 0.037 m/s. The velocity distribution showed faster-moving air in the collector and chimney sections, while the air moved more slowly in the drying chamber, as illustrated in Figures 8(c) and 8(d). The slower-moving air in the drying chamber may have been caused by frictional losses due to the large size of the maize ears. Supporting this observation, a study by Drienovsky, Anghel, and Sala (2019) reported that the typical diameter of maize ears at their centre ranges from 45.34 to 55.78 mm, which could contribute to airflow resistance on the tray within the drying chamber.

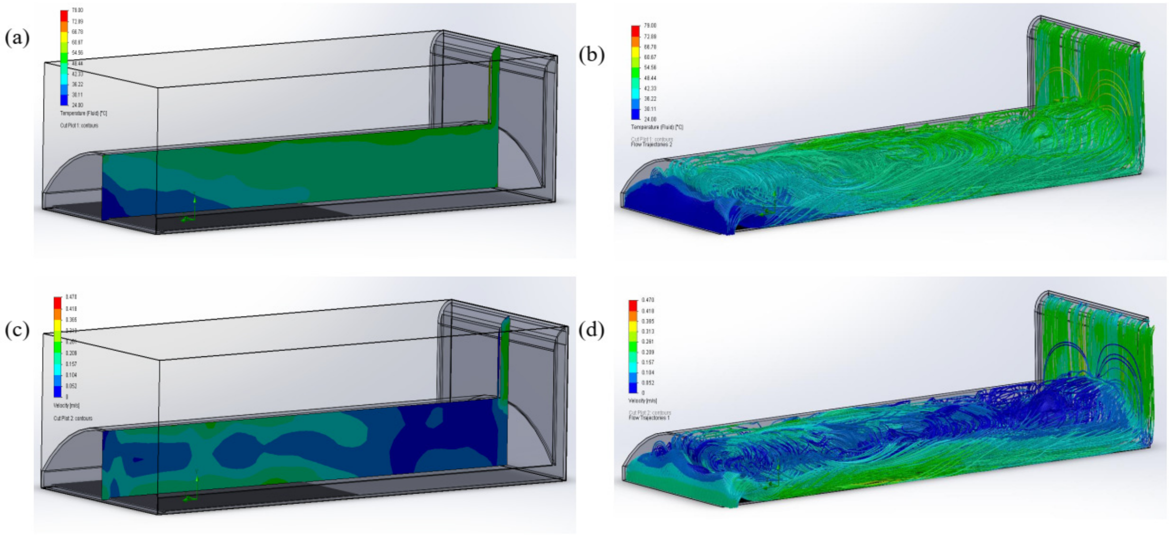

Figure 14. Temperature and velocity contours along with the flow trajectories

3.4 Economic Performance

The capital cost (materials and labour to build the dryer) was determined as ZMW 6,798.77 as shown in Table 3. The annual inflation rate and the interest rate in Zambia were taken as 15.2% and 13.5%, respectively (Trade Economics, 2024). Under these conditions, the payback period was found to be 3.7 years. This is slightly higher than the payback period of 0.25–3.26 years reported by Shimpy, Kumar, and Kumar (2023b) in their overview of various performance indicators used for the evaluation and analysis of solar dryers. In our study, it is noted that with the 10-year lifespan and the 3.7-year payback period of the dryer, the last 6.3 years of the use of the dryer are free of any payment, making this investment attractive.

Table 3. Parameters for determining the economic performance

Item	Amount
Capital Cost (ZMW)	6,798.77
Savings after one year (ZMW)	2,029.10
Inflation Rate (%)	15.2
Interest Rate (%)	13.5
Payback Period (Years)	3.7

4. Conclusion

The natural convection solar dryer designed in this study has demonstrated efficient drying performance, achieving a significant reduction in moisture content in maize ears from 23.4% to a safe storage level of 12.5% within five days, compared to twelve days with open sun drying. The temperature and airflow patterns within the dryer were found to be closely related to solar radiation levels, with average internal temperatures effectively maintained higher than the ambient, thus supporting adequate airflow and drying efficiency. Although exergy analysis indicated substantial exergy loss primarily due to irreversibility in the drying chamber, it suggests that dryer performance could be enhanced by increasing chimney height to boost airflow and improve exergy utilization. Computational Fluid Dynamics (CFD) analysis further supported the design by illustrating effective air heating and velocity distribution within the dryer, though airflow was somewhat restricted by maize ear size, resulting in high frictional losses.

Economically, the dryer presents a viable investment with a payback period of 3.7 years, after which it provides profitable use for the remainder of its ten-year lifespan. Although this payback period is slightly higher than those reported in other studies, the dryer remains economically attractive, especially in regions with high solar insolation. Overall, the results of this study demonstrate that the natural convection solar dryer is both technically and economically effective for drying maize ears and has the potential to be applied or modified for other agricultural products, contributing to sustainable post-harvest processing in rural areas.

It is noted that the contribution of solar dryers to sustainable post-harvest processing is influenced by challenges related to their implementation in different agricultural contexts. The following measures are recommended to mitigate these challenges:

(1) Customize solar dryer designs to suit local conditions such as climate, crops, and the quantity of produce to be dried.

(2) Use locally available, durable, and weather-resistant materials to reduce the cost of solar dryers while improving their lifespan.

(3) Train farmers on the operation, maintenance, and benefits of solar dryers. Educate them on drying techniques to ensure optimal drying performance and product quality.

(4) Provide financial support to smallholder farmers through subsidies or grants to make solar dryers more affordable. Encourage partnerships between governments, NGOs, and the private sector to share costs and provide technical support.

(5) Improve efficiency by implementing advanced designs, such as hybrid solar dryers with backup heating, to ensure continuous drying even during periods of low solar radiation. Optimise airflow and temperature distribution using Computational Fluid Dynamics (CFD).

(6) Promote awareness of the economic and environmental benefits of solar drying through agricultural extension services and media. Demonstrate the effectiveness of solar dryers through pilot projects and case studies.

(7) Integrate solar drying with broader agricultural value chains to ensure processed crops meet market standards for moisture content and quality. Provide support for storage, packaging, and marketing to enhance the profitability of solar-dried products.

(8) Advocate for policies that promote renewable energy solutions, including solar dryers, as part of sustainable agriculture programs. Establish quality standards for solar dryers to ensure reliability and performance.

(9) Conduct ongoing research and development to improve the design, efficiency, and affordability of solar dryers for diverse agricultural contexts. Collaborate with universities and research institutions to test and validate innovative solar drying technologies.

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