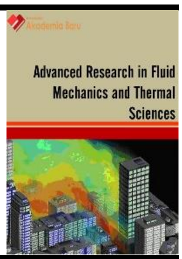
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879




# Experimental Analysis of Corn Drying in A Sustainable Solar Dryer

Open Access

Gisele Mol da Silva[1,2], André Guimarães Ferreira[2], Rogério Morouço Coutinho[2], Cristiana Brasil Maia[1,*]

[1] Pontifícia Universidade Católica de Minas Gerais - PUC Minas - Av. Dom José Gaspar, 500. Belo Horizonte. MG. Brasil
[2] Centro Federal de Educação Tecnológica de Minas Gerais - CEFET/MG - Av. Amazonas, 5253. Belo Horizonte. MG. Brasil

**ARTICLE INFO**

***Article history:***
Received 24 November 2019
Received in revised form 30 December 2019
Accepted 31 December 2019
Available online 18 March 2020

***Keywords:***
Solar drying; drying efficiency; energetic analysis

**ABSTRACT**

An energy analysis of corn grains drying was carried out to assess the performance of a forced-ventilation solar-cabin hybrid dryer. The major components of the dryer are a PV system, a solar collector and a drying chamber. Two fans were used to generate the forced-convection airflow and an electrical heater was used to ensure that the products will not reabsorb water from the airflow, by keeping the airflow temperayure always higher than ambient temperature. A sustainable drying was accomplished with the use of ~~a~~ the PV system to feed the fans and the electrical heater. The corn grains were dried from a moisture content of 23% to 13% in 8.5 h, with average thermal and drying efficiencies of 27% and 6%, respectively.



## 1. Introduction

Cereal grains are able to provide more energy to humankind than other crops [1]. Among the cereal grains, maize or corn is the leading cereal crop in terms of worldwide production and consumption [2-3]. Much of it becomes livestock feed (human or animal), biofuel or other value-added industrial products. World grain production is led by the United States, China, and Brazil. The crops need to be harvest as soon as they reach maturity because they lose quality if left un-harvested. In spite of massive production, postharvest losses during storage remain a significant challenge [4]. One of the most critical physiological factors to grain storage is its moisture content. Moisture content in the growing crop is naturally high and starts to decrease as the crop reaches maturity.

Drying is the process of moisture removal, reducing water activity from a product and assuring the microbial stability and guarantying the expected shelf-life of the product. The removal of moisture allows the product to be stored for a long time without deterioration. Furthermore, the processing of some products requires the reduction of the moisture content to lower values.

* *Corresponding author.*
*E-mail address: cristiana@pucminas.br (Cristiana Brasil Maia)*

When the corn reaches physiological maturity, its moisture content ranges from 30-38%. According to Magalhães and Durães [5], harvesting should occur when corn reaches a moisture content between 18 and 25%, if corn is submitted to drying processes before storage. The ideal moisture content for corn storage should be less than 13.5% to interrupt the fungal growth, which can cause deterioration of the grain, reduces the weight of grain, produces off-flavors and several mycotoxins [4].

Open sun drying is an economical method used for drying and preservation of agricultural products [6], but it has several limitations like the exposure of the products to rain, wind, moisture, and dust; loss of productivity due to birds and animals and deterioration due to insect attacks and fungi [7]. Dryers arise as an interesting alternative to reduce the drawbacks of open sun drying and are classified into solar, artificial and hybrid dryers. The use of renewable energy sources to dry agricultural products is a good approach. Most rural areas lack access to modern energy and are either too far from the main cities or not connected to the centralized national grid [8]. Also, for many farmers, it is too expensive to use electricity or fossil fuel to make crop drying in rural areas [9]. Among renewable sources, solar energy is a clean, cheap, effective and inexhaustible source [6], becoming increasingly attractive to dry agricultural products [10].

Solar dryers use only the energy from the sun to perform drying, and the final quality of dried products can be affected by the intermittence of climatic conditions, like solar radiation, temperature, and relative humidity. The use of solar energy is important to reduce the consumption of fossil fuels and has been studied by several researchers [11-13]. . Solar dryers are extensively studied in the literature [14-23]. In artificial dryers, the drying airflow conditions can be controlled, ensuring high final quality. Nevertheless, since drying is an energy-intensive process, the costs might be unfeasible. Some artificial dryers are described by perious works [24-26].

According to Lamidi *et al.,* [8], sustainable drying refers to the drying of an agricultural product with little or no fossil. Hybrid dryers combine solar energy with a conventional or some auxiliary source of energy as electricity, biomass or other fuel [6] to overcome the drawbacks of solar and artificial dryers. Photovoltaic thermal systems were used [27-29], biomass was used [9], [30] and LPG was used [31]. To the best knowledge of the authors, hybrid dryers using a PV system to generate electric power to dry corn grains were not studied. The drying of corn was studied by a few authors, but under different conditions than presented in this paper. In Rahmanian-Koushkaki *et al.,* [32], a hot air-infrared dryer was used to evaluate the grain moisture variation, for different inlet air temperatures, infrared radiation intensities and modes of drying bed. Shelled corn was dried in a plug flow fluidized bed dryer by Khanali *et al.,* [33] at different dry solid mass flow rates, drying air temperatures and weir heights, in order to use experimental data to validate a differential model of the dryer. Corn kernel was dried using hot air by Wei *et al.,* [34] to obtain experimental data to validate three-dimensional drying models to describe the temperature and moisture distribution in the germ and endosperm. Details about the dryer were not given by the authors. In this paper, it was evaluated the drying of corn in a sustainable forced-ventilation solar cabin hybrid dryer. A solar photovoltaic (PV) system was combined with the solar thermal collector to offset the shortcoming of the solar system. A PV system feeds the forced ventilation fans and an electrical heater. Also, the PV system was used to preheat the drying air before it reaches the solar collector, which was not described in any paper. The thermal efficiency of the dryer was evaluated for the drying of corn grains.

## 2. Methodology
### *2.1 Material*

The corn grains used in this study were obtained from Embrapa (Brazilian Agricultural Research Corporation), cultivated in a farm in Sete Lagoas (75 km from Belo Horizonte), Brazil. The initial moisture content of the grains was determined by placing a sample inside a stove (NI 1512 Nova Instrument) for 24 hours, at 105°C, and measuring its initial and final weight using a digital balance, as recommend by REEB and MILOTA [35]. The average initial moisture content was obtained to be 23% w.b. 16 kg of hybrid corn, hard type, in grains, were used in the experiment.

### *2.2 Experimental Prototype*

The system is classified as a forced convection type. A schematic diagram is shown in Figure 1. It consists of a solar collector, a drying chamber, fans, an electrical heater, and a PV system.

The dryer is 1800 mm long, 1000 mm wide and 500 mm high. It is structured in wood with a metal housing of galvanized steel.

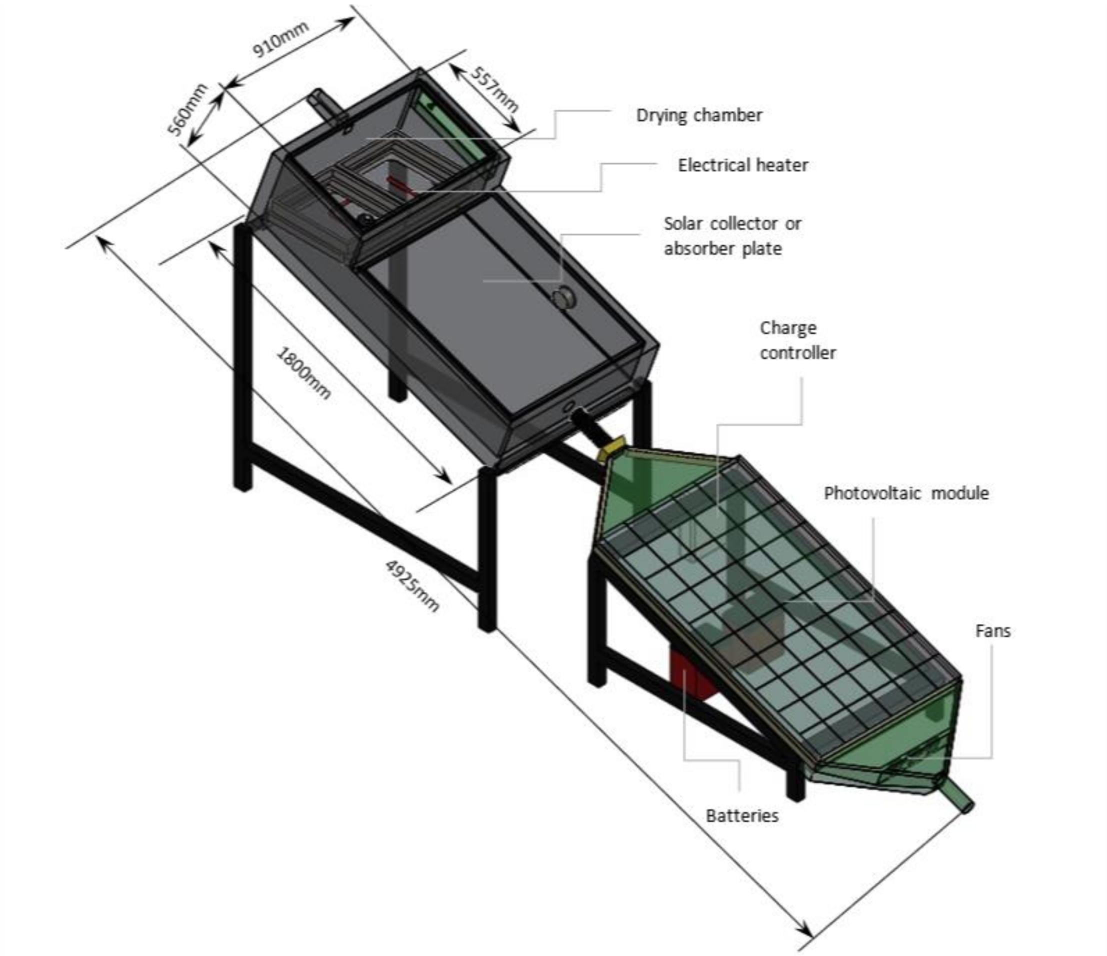



**Fig. 1.** Schematics of the dryer

The solar collector is positioned at the lower inner part of the structure, painted in black to maximize the absorption of the incident solar radiation. The air is forced into the dryer by two fans (of 5 W each) located at the dryer outlet. In order to ensure the system functioning during periods of a low incidence of solar radiation or at night, an electrical heater was installed inside the dryer, below the trays. A system comprised a PV system, a charge controller and two batteries to feed the fans and the electrical heater, allowing the system to operate without any input of external electricity.

The airflow is forced by the fans and the air enters the dryer through a rectangular screened opening. An electrical heater of 60 W was installed at the end of the plate, under the lower trays. It operates only to avoid moisture reabsorption by the corn. When there is little or no solar incidence, and the airflow temperature decreases below ambient temperature, the electrical heater is triggered and heats the drying airflow. The grains are placed in trays inside the drying chamber. After passing over the drying chamber, wet air leaves the system through a circular tube.

### *2.3 Experimental Procedure*

The solar drying system was installed at CEFET-MG, Belo Horizonte (20°S latitude and 44°W longitude). The city has great solar energy potential, with an annual mean temperature between 20-22°C [36] and a yearly average daily total radiation of 16 MJ/m$^2$ day [37]. The drying system was housed on the roof of a building of CEFET-MG, in a flat and unshaded surface, and supported by a metallic structure, which prevents its contact with the floor humidity. The solar collector surface was tilted 20° (equals local latitude) and faced north, to maximize the incident irradiation throughout the year [38]. The experiments were performed on September 26, 2018, corresponding to the spring equinox in the southern hemisphere, starting at 7:30 AM and lasting 24 hours. The electrical heater operated only from 5:30 PM to 7:30 AM, when the incidence of solar radiation was low. 16 kg of corn grains were dried during the experiment. For comparison, open sun drying was performed at the same time. The temperature of the air in different locations of the drying system was measured with K-type thermocouples during the experiments. The relative humidity of air at the inlet and outlet of the dryer was measured with a thermo-psychrometer (AKSO, AK174 model). The velocity of air at the outlet was measured with an anemometer (ICEL, NA-4870 model). The incident solar radiation was measured with a pyranometer (Hukseffux thermal sensor, SR05, DA2 model). The samples of corn were weighted with a digital electronic balance (Toledo, 9094 model, 6 kg of capacity and 1g of accuracy). The uncertainty analyses were performed based on the following equations, according to researchers [39], and also described by references [40-41].

The arithmetic mean of the measurements $X_m$ is given by

$$X_m = \frac{1}{N}\sum X_i \tag{1}$$

N is the number of measurements, $X_i$ is the ith measurement of the parameter.

The standard deviation s is given by

$$s = \sqrt{\frac{1}{N-1}\sum(X_i^2 - X_m^2)} \tag{2}$$

The sensitivity a is given by

$$a = \frac{1}{\sqrt{N}} \tag{3}$$

The uncertainty U is given by:

$$U = \sum_{i=1}^{R} a_i^2 \cdot s_i^2 \tag{4}$$

### 2.4 Mathematical Model

The energy analysis of the drying system was accomplished based on mass and energy conservation equations [42]. The basic data requirements were given by experimental data. The mass conservation equation can be expressed as

$$(\dot{m}_{da})_{in} = (\dot{m}_{da})_{out} = \dot{m}_{da} \tag{5}$$

$$\left(\dot{m}_{st_{H_2O}}\right)_{in} + \left(\dot{m}_{st_{H_2O}}\right)_{p} = \left(\dot{m}_{st_{H_2O}}\right)_{out} \quad or \quad w_{in}\dot{m}_{da} + \left(\dot{m}_{st_{H_2O}}\right)_{p} = w_{out}\dot{m}_{da} \tag{6}$$

where $\dot{m}_{da}$ , $(\dot{m}_{da})_{in}$ , $(\dot{m}_{da})_{out}$ , $\left(\dot{m}_{st_{H_2O}}\right)_{in}$, $\left(\dot{m}_{st_{H_2O}}\right)_{out}$ $and$ $\left(\dot{m}_{st_{H_2O}}\right)_{p}$ represent, respectively, the mass flow rate of the dry air, of the dry air at the inlet and outlet of the drying system, of the humidity at the inlet and outlet of drying system inlet, and of the humidity of the product [kg/s]. $w_{in}$ and $w_{out}$ represent the air absolute humidity at the inlet and outlet of the drying system, respectively [kg of water/kg of dry air].

Neglecting the mechanical work in the process, the first law of thermodynamics can be expressed as:

$$0 = \dot{Q} + \sum_{in} \dot{m} \left(h + \frac{1}{2}v^2 + gz\right) - \sum_{out} \dot{m} \left(h + \frac{1}{2}v^2 + gz\right) \tag{7}$$

where $\dot{Q}$ is the heat transfer [W], $\dot{m}$ is the air mass flow rate [kg/s], $h$ is the specific enthalpy [J/kg], $\frac{1}{2}v^2$ the specific kinetic energy [m$^2$/s$^2$] and $gz$ the specific potential energy [m$^2$/s$^2$]. It is worth noting that, although some authors [42-43] neglect the effects of kinetic and potential energies on their analyses, in this study they were not neglected.

The heat transfer inflow refers to the solar radiation transferred to the system by (a) the PV system (b) the absorber plate and (c) the top surface of the drying chamber.

The thermal efficiency is the ratio of the energy expended to the energy supplied and is given by

$$\eta_I = \frac{\sum_{out} \dot{m}\left(h+\frac{1}{2}v^2+gz\right) - \sum_{in} \dot{m}\left(h+\frac{1}{2}v^2+gz\right)}{(A_m+A_a+A_c)G} \times 100\% \tag{8}$$

where $A_m$, $A_a$ and $A_c$ represent, respectively, the areas of the PV system top surface, the glass top surface of the absorber plate and the glass top surface of the drying chamber [m$^2$] and $G$ is the solar irradiation [kW/m$^2$]. The energy supplied refers to the solar radiation on the PV system, absorber plate and drying chamber.

The drying efficiency is the ratio of the energy used to evaporate the product moisture to the energy supplied, given by Fudholi *et al.,* [20]

$$\eta_{III} = \frac{m_{H2O} L}{\int (A_m+A_a+A_c)\, G\, dt} \times 100\% \tag{9}$$

where $m_{H2O}$ is the water mass removed from the product [kg] and $L$ is the water vaporization latent heat [kJ/kg].

The initial wet basis moisture content of the corn can be expressed as [44]

$$W_{sp} = \frac{(m_{sp})_i - (m_{sp})_e}{(m_{sp})_i} \times 100 \quad (10)$$

where $(m_{sp})_i$ and $(m_{sp})_e$ represent, respectively, the initial and final mass of the sample placed in the oven [kg].

The instantaneous wet basis moisture content is given by Ferreira *et al.,* [25]

$$W_x = 100 - \left[\frac{(m_p)_i}{(m_p)_x}(100 - W_{sp})\right] \quad (11)$$

where $(m_p)_i$ and $(m_p)_x$ are, respectively, the initial and the instantaneous product mass [kg].

The specific moisture extraction rate (SMER) is given by Stawreberg and L. Nilsson [45] and Darvishi *et al.,* [46].

$$\text{SMER} = \frac{m_{wi} - m_{wo}}{Q_{tot}} \quad (12)$$

where $m_{wi}$ and $m_{wo}$ represent, respectively, the mass of the product in the beginning and end of ghe drying process and $Q_{tot}$ represent the total energy supply.

## 3. Results

The drying experiments were performed during the Spring equinox (September 26th). The variations in solar radiation and ambient temperature are shown in Figure 2. The maximum solar radiation recorded was (1020 ±11) W/m$^2$, recorded at 12:00, and the average solar irradiance was 680 W/m$^2$ . The ambient temperature ranged from 27-33°C, with an average value of 30°C.

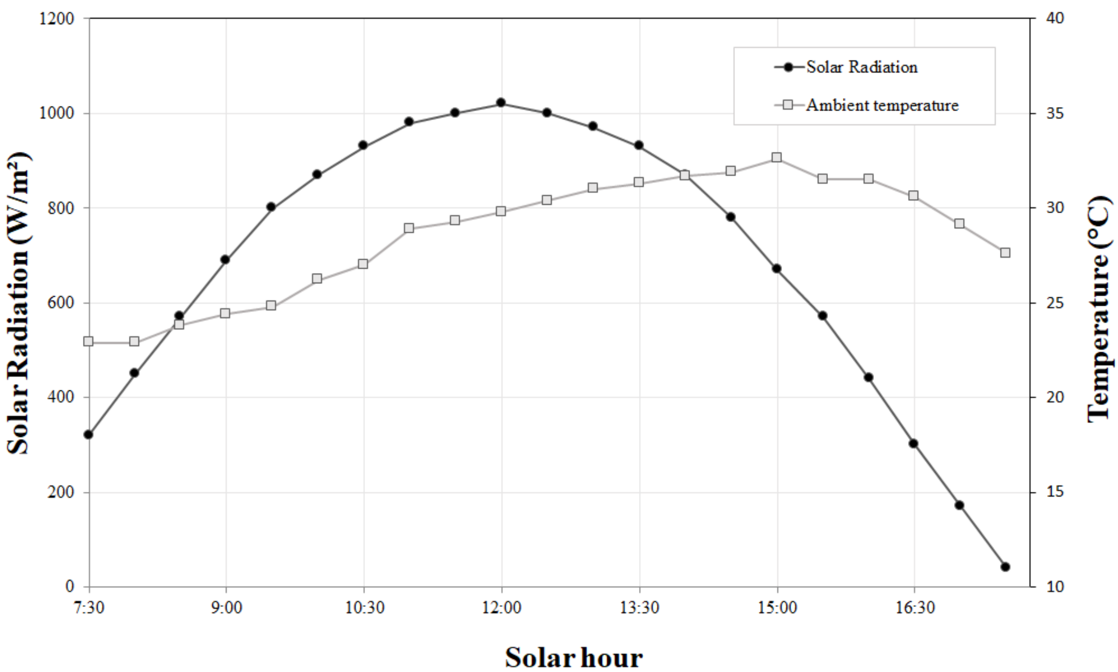



**Fig. 2.** Solar radiation and ambient air temperature variation with time

Figure 3 and 4 present the inlet and outlet temperature and relative humidity variations during the experimental tests. The outlet air temperature varies in accordance with the variation of ambient temperature and solar radiation, and, as expected, temperature and relative humidity showed opposite trends. It was observed that the temperatures increased continuously until approximately 2:30 PM. The maximum temperature difference between outlet and inlet (ambient) temperature was 26°C. Until 5:30 PM, the increase in the outlet air temperature was provided only by the solar radiation incident on the absorber plate and on the drying chamber. After 5:30 PM, the electrical heater was on, and if the airflow temperature drops below ambient temperature, it heats the airflow, ensuring that the airflow relative humidity is always lower than ambient relative humidity and that the corn does not reabsorbs water. At night, when there is no incidence of solar radiation, the ambient and airflow temperatures decrease and the relative humidities increase.

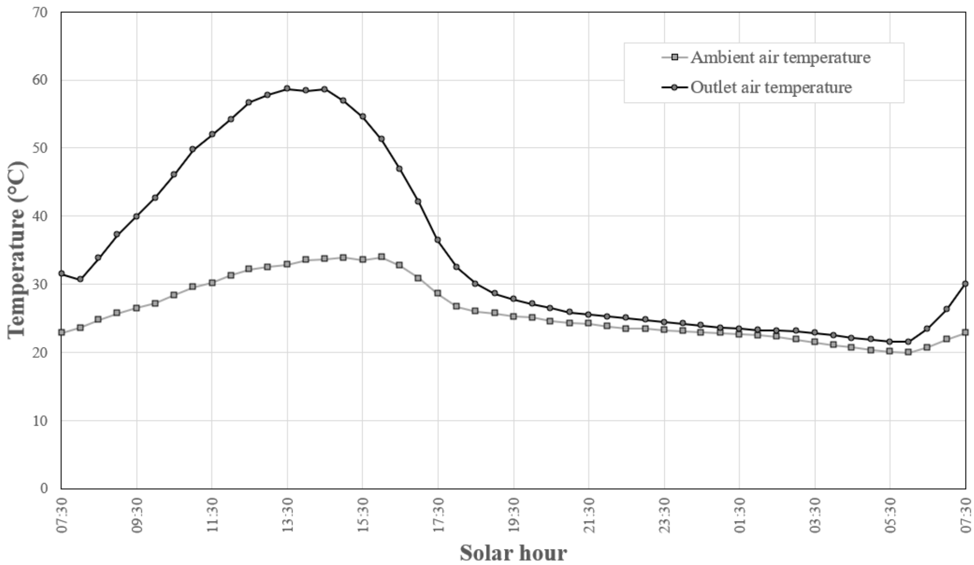



**Fig. 3.** Inlet and outlet air temperatures variation with time

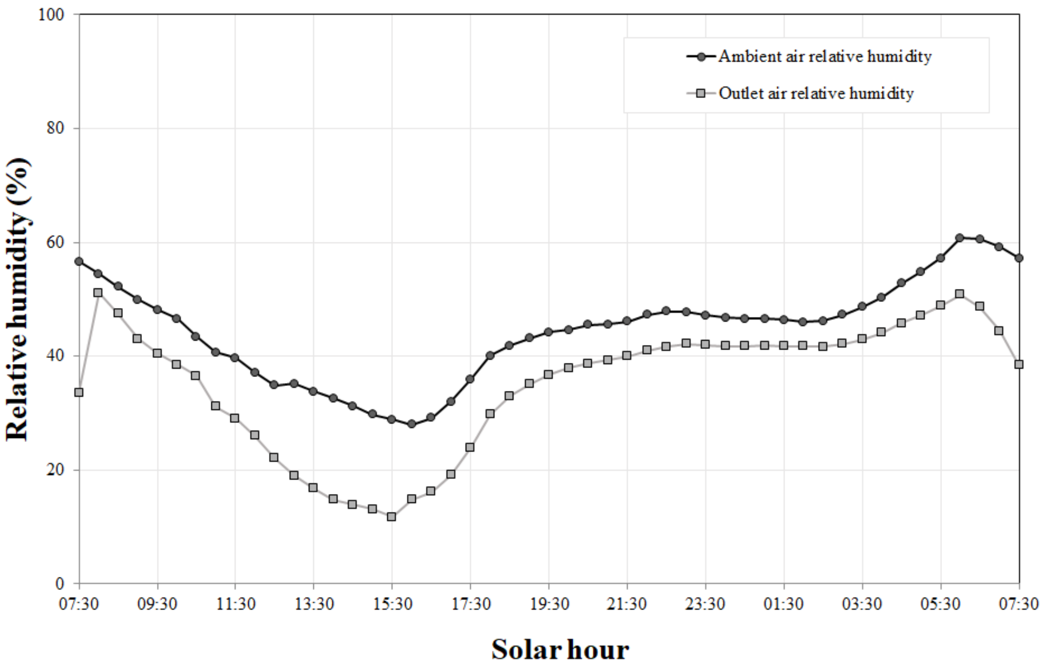



**Fig.4.** Inlet and outlet air relative humidity variation with time

The drying experiment with corn was carried out by drying 16 kg of corn grains. The corn was dried in 8.5 h from the initial moisture content of 23.0% (w.b.) to the final desired moisture content of 13% (w.b.), as seen in Figure 5. The final moisture content represents equilibrium moisture between the corn and the drying air, beyond which any changes in the mass of corn could not occur [22]. It can be seen that the sample exposed to natural sun drying was not able to reach the desired moisture content of 12.6% in 24 h of tests. The shorter drying time in the dryer occurred as a result of increased heat supply to the product, which got energy from the PV module, the collector and incident solar radiation, while the samples exposed to natural sun drying got energy only from the incident solar radiation. The drying rate of the natural sun drying decreased when the moisture content reached 16% (w.b.), because the corn presented reduced humidity, requiring a higher thermal input to remove more water from the products.

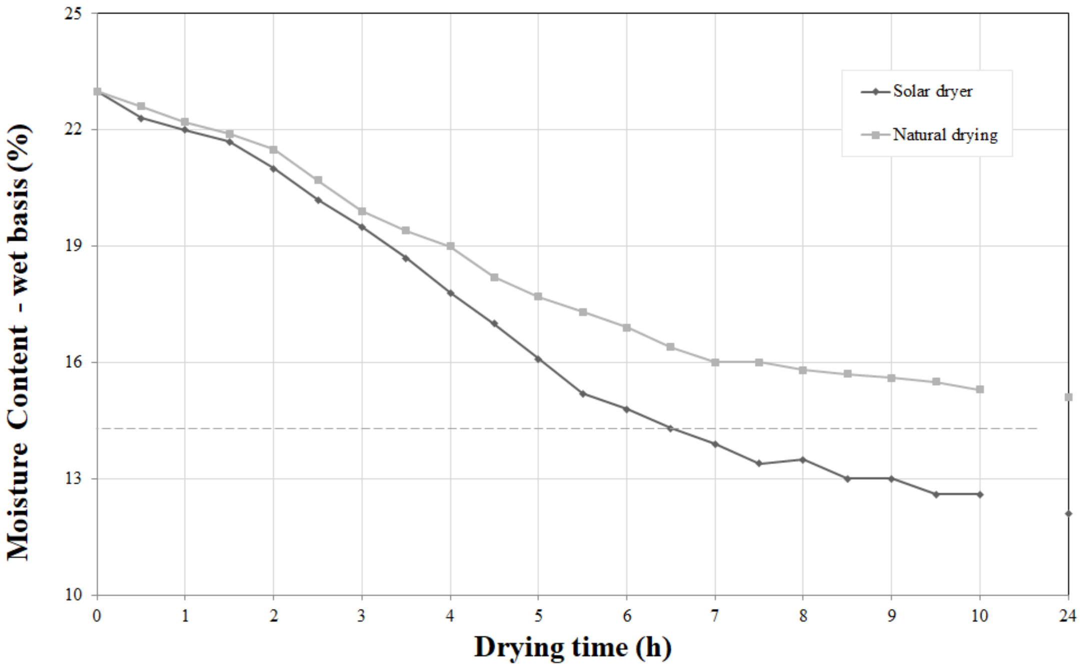



**Fig. 5.** Drying curves

Time-dependent change of thermal efficiency of the system is shown in Figure 6, together with the incident solar radiation. Since the experiment was performed on a clear day, solar radiation and thermal efficiency did not present significant fluctuations. Thermal efficiency varied in accordance with incident solar radiation and airflow temperature, since, for a constant airflow velocity, higher air temperature results in higher thermal efficiency [47]. It can be noticed a sudden increase on the thermal efficiency at the end of the day, due to the resuction of incidentsolar radiation. According to Eq. (7), thermal efficieny is affected both by the enthalpy difference between outlet and inlet air and incident solar radiation.At the end of the day, the incident solar radiation decreased, but the thermal inertia of the system enabled the airflow to remain heated, still creating a high enthalpy difference. Combining high enthalpy differences to low solar radiation, high efficiency is found.

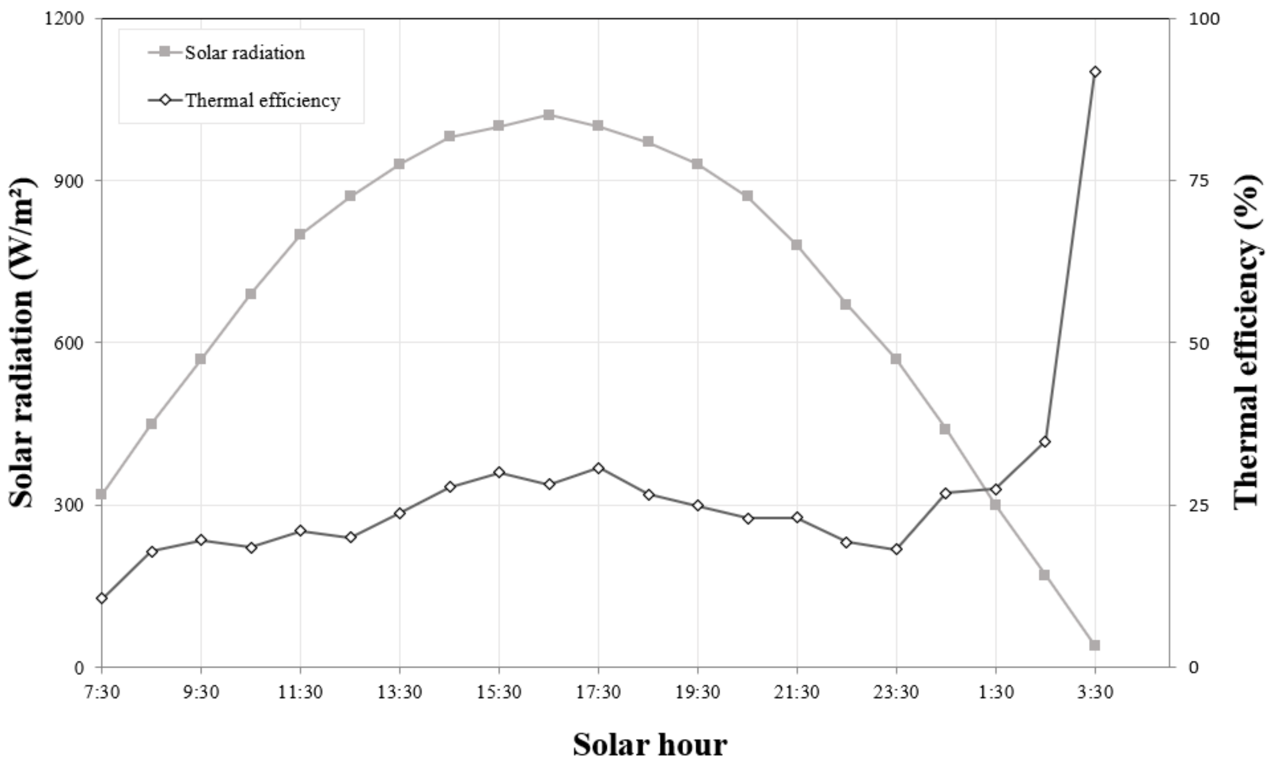



**Fig. 6.** Thermal efficiency variation with time

The minimum thermal efficiency was (10.6 ± 0.6) % and the maximum thermal efficiency was (92 ± 6)%, with an average value of 26.8%. The average drying efficiency was (6.1 ± 0.1) % when the moisture content was reduced from (23.0 ± 0.5) % to (12.6 ± 0.1) %. The specific moisture extraction rate was 1.3 kg/kWh. This value is consistent with experimental data reported in the literature. No information was found for this SMER for corn drying, but values ranging from 0.12 to 1.28 kg/kWh were found for general hot-air drying, 0.72-1.2 for vaccum drying and 1.0-4.0 for heat pump drying [48]. Also, SMER ranging from 0.65 to 1,75 were found for drying of apple, guava and potato [49]. Higher SMER values indicate an efficient drying process with low energy losses. Increasing the air velocity and the amount of products inside the dryer can improve the SMER [50].

## 4. Conclusions

In this study, we evaluated a sustainable forced-ventilation solar-cabin hybrid dryer. Corn grains were dried successfully in the dryer, and energy analysis of the drying process was performed. The experimental results indicated that:

i. The solar dryer was able to operate continuously without any external power input. The PV system fed fans and, when needed, the electrical heater.
ii. The average thermal and drying efficiencies were about 27% and 6%, respectively, at the average solar radiation of about 680 W/m$^2$ and average ambient temperature of 30°C.
iii. There was observed a high thermal efficiency at the end of the day, caused by the thermal inertia of the system, which kept the airflow with a higher temperature difference related to inlet temperature, when the incident solar radiation decreased.
iv. The maximum temperature increased in the system was 27°C.
v. The results of the study showed that the dryer can be used in small farms, located away from the electricity grid.

## Acknowledgment
This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. The authors are also thankful to FAPEMIG, CNPq, CEFET-MG and PUC Minas.

## References
[1] Awika, Joseph M. "Major cereal grains production and use around the world." In *Advances in cereal science: implications to food processing and health promotion*, pp. 1-13. American Chemical Society, 2011.
[2] de Lima, Rafael Friedrich, Rafael Gomes Dionello, Maria do Carmo Ruaro Peralba, Simone Barrionuevo, Lauri Lourenço Radunz, and Francisco Wilson Reichert Júnior. "PAHs in corn grains submitted to drying with firewood." *Food chemistry* 215 (2017): 165-170.
[3] Serna-Saldivar, Sergio O., and Esther Perez Carrillo. "Food uses of whole corn and dry-milled fractions." In *Corn*, pp. 435-467. AACC International Press, 2019..
[4] Suleiman, R., C. J. Bern, T. J. Brumm, and K. A. Rosentrater. "Impact of moisture content and maize weevils on maize quality during hermetic and non-hermetic storage." *Journal of Stored Products Research* 78 (2018): 1-10.
[5] Magalhaes, Paulo C., and Frederico OM Durães. "Fisiologia da produção de milho." *Embrapa Milho e Sorgo-Circular Técnica (INFOTECA-E)* (2006).
[6] Kumar, Mahesh, Sunil Kumar Sansaniwal, and Pankaj Khatak. "Progress in solar dryers for drying various commodities." *Renewable and Sustainable Energy Reviews* 55 (2016): 346-360..
[7] Sharma, Atul, C. R. Chen, and Nguyen Vu Lan. "Solar-energy drying systems: A review." *Renewable and sustainable energy reviews* 13, no. 6-7 (2009): 1185-1210.
[8] Lamidi, Rasaq O., Long Jiang, Pankaj B. Pathare, YaoDong Wang, and A. P. Roskilly. "Recent advances in sustainable drying of agricultural produce: A review." *Applied Energy* 233 (2019): 367-385.
[9] Yassen, Tadahmun A., and Hussain H. Al-Kayiem. "Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer." *Solar Energy* 134 (2016): 284-293.
[10] Fudholi, Ahmad, Kamaruzzaman Sopian, Mohd Yusof Othman, and Mohd Hafidz Ruslan. "Energy and exergy analyses of solar drying system of red seaweed." *Energy and Buildings* 68 (2014): 121-129.
[11] Hashim, Ghasaq Adheed, and NA Che Sidik. "Numerical study of harvesting solar energy from small-scale asphalt solar collector." *Journal of Advanced Research Design* 2, no. 1 (2014): 10-19.
[12] Maia, Cristiana B., Felipe VM Silva, Vinícius LC Oliveira, and Lawrence L. Kazmerski. "An overview of the use of solar chimneys for desalination." *Solar Energy* 183 (2019): 83-95.
[13] Maia, Cristiana B., André G. Ferreira, and Sérgio M. Hanriot. "Evaluation of a tracking flat-plate solar collector in Brazil." *Applied thermal engineering* 73, no. 1 (2014): 953-962.
[14] Wang, Wei, Ming Li, Reda Hassanien Emam Hassanien, Yunfeng Wang, and Luwei Yang. "Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango." *Applied Thermal Engineering* 134 (2018): 310-321.
[15] Singh, Shobhana, and Subodh Kumar. "New approach for thermal testing of solar dryer: development of generalized drying characteristic curve." *Solar energy* 86, no. 7 (2012): 1981-1991..
[16] Fterich, M., H. Chouikhi, H. Bentaher, and A. Maalej. "Experimental parametric study of a mixed-mode forced convection solar dryer equipped with a PV/T air collector." *Solar Energy* 171 (2018): 751-760.
[17] Téllez, Margarita Castillo, Isaac Pilatowsky Figueroa, Beatríz Castillo Téllez, Erick C. López Vidaña, and Anabel López Ortiz. "Solar drying of Stevia (Rebaudiana Bertoni) leaves using direct and indirect technologies." *Solar Energy* 159 (2018): 898-907.
[18] Chaouch, Wafa Braham, Abdellah Khellaf, Ahmed Mediani, Mohamed El Amine Slimani, Akil Loumani, and Abdelkader Hamid. "Experimental investigation of an active direct and indirect solar dryer with sensible heat storage for camel meat drying in Saharan environment." *Solar Energy* 174 (2018): 328-341.
[19] Mehta, Pranav, Shilpa Samaddar, Pankaj Patel, Bhupendra Markam, and Subarna Maiti. "Design and performance analysis of a mixed mode tent-type solar dryer for fish-drying in coastal areas." *Solar Energy* 170 (2018): 671-681.
[20] Fudholi, Ahmad, Kamaruzzaman Sopian, Mohammad H. Yazdi, Mohd Hafidz Ruslan, Mohamed Gabbasa, and Hussein A. Kazem. "Performance analysis of solar drying system for red chili." *Solar Energy* 99 (2014): 47-54.
[21] Rabha, D. K., P. Muthukumar, and C. Somayaji. "Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger." *Renewable Energy* 105 (2017): 764-773.
[22] Karthikeyan, A. K., and S. Murugavelh. "Thin layer drying kinetics and exergy analysis of turmeric (Curcuma longa) in a mixed mode forced convection solar tunnel dryer." *Renewable Energy* 128 (2018): 305-312.
[23] El Khadraoui, Aymen, Salwa Bouadila, Sami Kooli, Abdelhamid Farhat, and Amenallah Guizani. "Thermal behavior

of indirect solar dryer: Nocturnal usage of solar air collector with PCM." *Journal of cleaner production* 148 (2017): 37-48.

[24] Amjad, Waseem, Oliver Hensel, Anjum Munir, Albert Esper, and Barbara Sturm. "Thermodynamic analysis of drying process in a diagonal-batch dryer developed for batch uniformity using potato slices." *Journal of food engineering* 169 (2016): 238-249.

[25] Ferreira, André Guimarães, Lindomar Matias Gonçalves, and Cristiana Brasil Maia. "Solar drying of a solid waste from steel wire industry." *Applied thermal engineering* 73, no. 1 (2014): 104-110.

[26] Castro, María, Celia Román, Marcelo Echegaray, Germán Mazza, and Rosa Rodriguez. "Exergy analyses of onion drying by convection: influence of dryer parameters on performance." *Entropy* 20, no. 5 (2018): 310.

[27] Tiwari, Sumit, and G. N. Tiwari. "Thermal analysis of photovoltaic-thermal (PVT) single slope roof integrated greenhouse solar dryer." *Solar Energy* 138 (2016): 128-136.

[28] Tiwari, Sumit, and G. N. Tiwari. "Energy and exergy analysis of a mixed-mode greenhouse-type solar dryer, integrated with partially covered N-PVT air collector." *Energy* 128 (2017): 183-195.

[29] Ceylan, İlhan, Ali Etem Gürel, Alper Ergün, and Abdulsamed Tabak. "Performance analysis of a concentrated photovoltaic and thermal system." *Solar Energy* 129 (2016): 217-223.

[30] Borah, A., L. N. Sethi, S. Sarkar, and K. Hazarika. "Drying Kinetics of Sliced Turmeric (Curcuma longa L.) in a Solar-Biomass Integrated Drying System." *Journal of Food Processing and Preservation* 41, no. 3 (2017): e12904.

[31] López-Vidaña, Erick Cesar, Lilia L. Méndez-Lagunas, and Juan Rodríguez-Ramírez. "Efficiency of a hybrid solar–gas dryer." *Solar energy* 93 (2013): 23-31.

[32] Rahmanian-Koushkaki, H., A. Nourmohamadi-Moghadami, D. Zare, and G. Karimi. "Experimental and theoretical investigation of hot air-infrared thin layer drying of corn in a fixed and vibratory bed dryer." *Engineering in agriculture, environment and food* 10, no. 3 (2017): 191-197.

[33] Khanali, Majid, Asgar Khakpour Giglou, and Shahin Rafiee. "Model development for shelled corn drying in a plug flow fluidized bed dryer." *Engineering in agriculture, environment and food* 11, no. 1 (2018): 1-8.

[34] Wei, Shuo, Zhenhua Wang, Fenghe Wang, Weijun Xie, Pengxiao Chen, and Deyong Yang. "Simulation and experimental studies of heat and mass transfer in corn kernel during hot air drying." *Food and Bioproducts Processing* 117 (2019): 360-372.

[35] Reeb, James E., Michael R. Milota, and Western Dry Kiln Association. "Moisture content by the oven-dry method for industrial testing." (1999).

[36] Alvares, Clayton Alcarde, José Luiz Stape, Paulo Cesar Sentelhas, Gonçalves de Moraes, José Leonardo, and Gerd Sparovek. "Köppen's climate classification map for Brazil." *Meteorologische Zeitschrift* 22, no. 6 (2013): 711-728.

[37] Maia, Cristiana Brasil, André Guimarães Ferreira, Luben Cabezas-Gómez, Janaína de Oliveira Castro Silva, and Sérgio de Morais Hanriot. "Thermodynamic analysis of the drying process of bananas in a small-scale solar updraft tower in Brazil." *Renewable Energy* 114 (2017): 1005-1012.

[38] Duffie, John A., and William A. Beckman. "Solar Thermal Power Systems." *Solar Engineering of Thermal Processes, Fourth Edition, John Wiley & Sons, Inc., Hoboken, NJ, USA.*

[39] JCGM, JCGM. "Evaluation of measurement data—Guide to the expression of uncertainty in measurement." *Int. Organ. Stand. Geneva ISBN* 50 (2008): 134.

[40] Ceylan, İlhan, and Ali Etem Gürel. "Solar-assisted fluidized bed dryer integrated with a heat pump for mint leaves." *Applied Thermal Engineering* 106 (2016): 899-905..

[41] Kaya, Metin, Ali Etem Gürel, Ümit Ağbulut, İlhan Ceylan, Selim Çelik, Alper Ergün, and Bahadır Acar. "Performance analysis of using CuO-Methanol nanofluid in a hybrid system with concentrated air collector and vacuum tube heat pipe." *Energy Conversion and Management* 199 (2019): 111936.

[42] Dincer, Ibrahim, and Marc A. Rosen. *Exergy: energy, environment and sustainable development*. Newnes, 2012.

[43] Moran, Michael J., Howard N. Shapiro, Daisie D. Boettner, and Margaret B. Bailey. *Fundamentals of engineering thermodynamics*. John Wiley & Sons, 2010.

[44] Belessiotis, V., and E. Delyannis. "Solar drying." *Solar energy* 85, no. 8 (2011): 1665-1691.

[45] Stawreberg, Lena, and Lars Nilsson. "Modelling of specific moisture extraction rate and leakage ratio in a condensing tumble dryer." *Applied thermal engineering* 30, no. 14-15 (2010): 2173-2179.

[46] Darvishi, Hosain, Mohsen Azadbakht, and Bashir Norallahi. "Combination of closed loop-fluidized bed dryer and osmotic drying for processing of white mushroom: mass transfer, drying kinetics and specific moisture extraction rate." *International Journal of Green Energy* 16, no. 11 (2019): 847-855.

[47] Sansaniwal, Sunil Kumar, Vashimant Sharma, and Jyotirmay Mathur. "Energy and exergy analyses of various typical solar energy applications: A comprehensive review." *Renewable and Sustainable Energy Reviews* 82 (2018): 1576-1601.

[48] Chua, Kian J., Siaw K. Chou, and W. M. Yang. "Advances in heat pump systems: A review." *Applied energy* 87, no. 12 (2010): 3611-3624.

[49] Aktaş, Mustafa, İlhan Ceylan, and Sezayi Yilmaz. "Determination of drying characteristics of apples in a heat pump and solar dryer." *Desalination* 239, no. 1-3 (2009): 266-275.

[50] Şevik, Seyfi. "Experimental investigation of a new design solar-heat pump dryer under the different climatic conditions and drying behavior of selected products." *Solar Energy* 105 (2014): 190-205.