

# Numerical and Experimental Validation of Solar Tunnel Dryer for Drying Agricultural Products under Togo Climatic Conditions

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**Abstract** This paper presents the mathematical modelling and experimental validation of a solar tunnel dryer Hoheinhem -Type for drying maize in Togo climatic conditions. All the experimental tests were done in Gape Kpodzi city (6°42'N latitude and 1°21'W longitude), in South Togo, 88 km from Lomé, during the summer season. Solar dryers consist of an air collector, a drying chamber, and an air circulation system. Heated air in solar air collector was forced through the maizes by a blower. Yellow dent-type Maize was used for drying experiments. During the drying period, drying air temperature, relative humidity, airflow rates, solar radiation, and loss of mass were measured continuously at different levels of the dryer. The tunnel dryer is a metallic framed structure covered with a 200- $\mu$ m ultraviolet stabilized plastic sheet. The dryer works on mixed-mode convection, and the maximum temperature attained during the experiment was 58.11 °C. The air temperature at the collector outlet ranges from 32°C to 68°C. The solar tunnel dryer Hoheinhem-Type dried the Maize from an initial moisture content of 35% (wb) to 13% (wb) in 15 solar hours under typical Togo climatic conditions. A system of partial differential equations describing heat and moisture transfer during the drying of Yellow Maize in this solar tunnel dryer was developed and the system of nonlinear partial differential equations obtained was solved numerically by the finite difference method. The mathematical modelling was programmed in Fortran PGI version 2008. The simulated results agreed well with experiential data for solar drying of maize. Some additional parametric studies are presented and is shown that this model can be used to provide the design data and to optimize this type of drier.

**Keywords:** experimental style, mathematical modeling, solar tunnel dryer, simulation, solar drying of maize

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## 1. Introduction

Small-scale dried food industries are growing very fast in Western Africa, especially in Togo. Situated in favorable climate conditions, West African countries produce annually huge amounts of tropical fruits and vegetables. Drying is a major post-harvest processing of these food products. To respond to the demand for dried food from both domestic and international markets, several small-scale dried food industries have been developed in Western Africa. In Togo, some of these industries are established as community enterprises which are operated by villagers. To dry their products on a commercial scale, most community enterprises use cabinet tray dryers heated by using liquefied petroleum gas (LPG) burners. In some cases, the drying starts with the open-sun drying and continues with a cabinet tray dryer using an LPG burner. In the last few years, the price of LPG has

substantially increased, thus increasing the drying cost. As Togo is located in a tropical zone that receives abundant solar radiation, the country has tremendous potential for solar drying of fruits and vegetables [1,2].

In the last 40 years, many types of solar dryers have been developed in various countries [3,4]. Many studies on natural convection solar drying of agricultural products have been reported [3,4,5,6]. However, the success achieved by natural convection solar dryers has been limited due to low buoyancy-induced airflow. This has prompted researchers to develop a forced convection solar dryer. Also, many studies have been reported on forced convection solar dryers [7-14]. The intensive literature reviews on solar dryers can be found in [15,16]. From these reviews, it is noticed that most solar dryers have a small loading capacity and cannot function properly during cloudy or rainy periods. Consequently, it is not appropriate to use such dryers for the small-scale food industries in Togo.

In general, small-scale food industries in Togo require a

solar dryer which could be used to dry 3,000-5,000 kg of fruits or vegetables per batch. As Togo is situated in the tropics, the rainy season lasts approximately six months. Apart from high loading capacity, the dryer has to be equipped with an auxiliary heater to ensure continuous drying operation during the rainy season. To meet this requirement, we have developed a solar tunnel dryer type Hohenheim dryer for drying agricultural products in Togo. The dryer has a loading capacity of 3000 kg for cereals. Simulation of solar drying is essential to optimize the dimensions of solar drying systems and optimization techniques can be used for the optimal design of drying systems [17,18].

Many studies have been reported on the solar drying of fruits and vegetables but limited studies have been reported on the drying of agriculture products. Recently Assefa et al. [19] reported the drying of Ginger using the solar tunnel, but no systematic experimental and simulation study on solar drying yellow maize has been reported. This paper presents mathematical modelling and experimental validation of a solar tunnel dryer (STD) for drying agricultural products under Togo Climatic conditions.

## 2. Materials and Methods

### 2.1. Dryer Description

The dryer has been commissioned in the weather conditions of Togo in Gapé - Kpodji, (06°8.2488' N, 0 1°12.7362' E) for drying agricultural produce. The dryer used is a solar tunnel dryer of the Hohenheim type. It is a mixed solar dryer that is composed of a flat solar collector and a drying chamber where the products are arranged to be dried. The collector and the drying cabinet are glued one after the other as shown in figure 1. The flat collector consists mainly of a galvanized sheet metal absorber painted black and covered with a transparent plastic film. Air circulation in the dryer is maintained by two fans (12V; 1.2A) powered by a photovoltaic module (Salarex: 12V; 41.6W). The drying chamber comprising three compartments in series is covered by a transparent plastic film allowing solar radiation to reach the products.

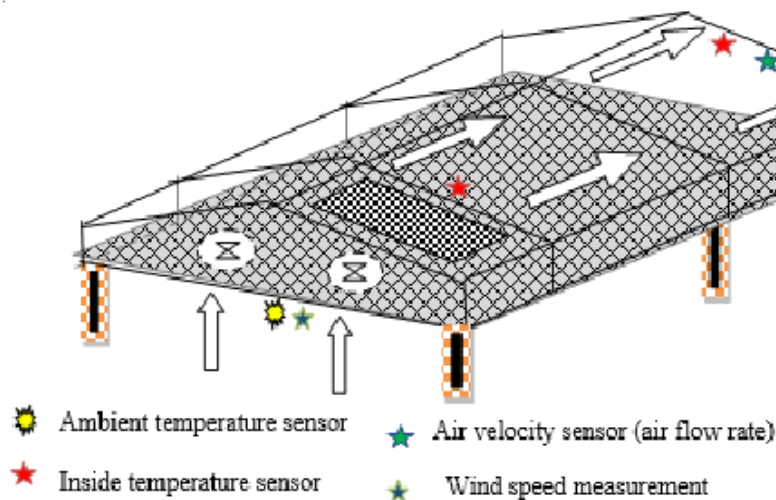


Figure 1. Experimental set-up solar tunnel dryer

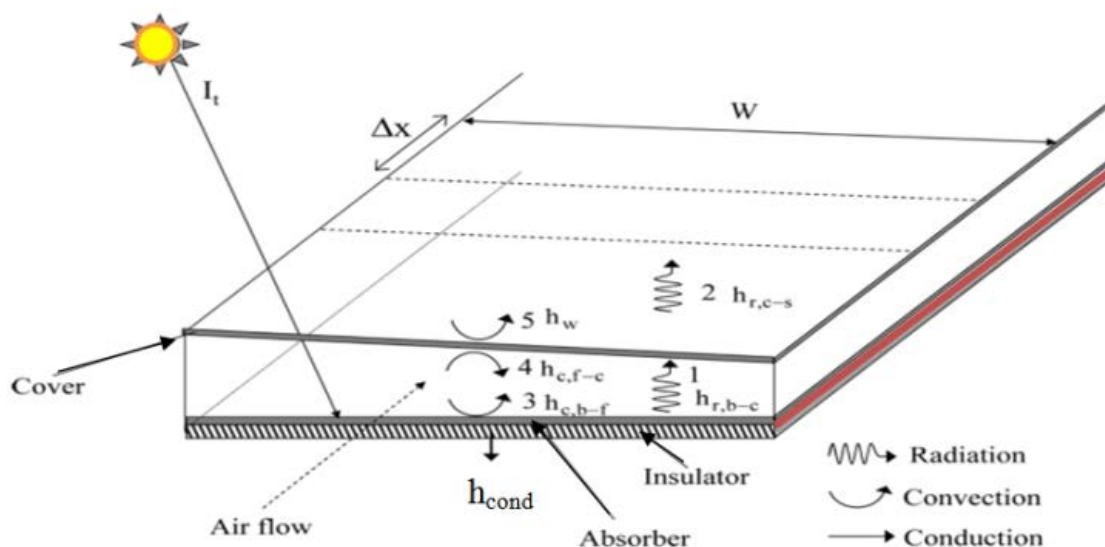


Figure 2. Different energy transfer in the solar collector

## 2.2. Experimental Setup

The solar tunnel dryer's performance was assessed in the running experiments with maize under climatical conditions in Togo. Air characteristics are measured every hour using temperature sensors, humidity, and air velocity. These sensors are installed in different points of the exposure unit: inlet, middle, and outlet as shown in figure 1. These sensors are connected to the data acquisition unit Almemo 2250 allowing automatic data recording. The weather data is provided by the weather service of Togo. Four sets of experiments were conducted in September 2015 under the climate conditions of South Togo. From 8:00 a.m. to 6:00 p.m. all measurable data (drying air temperature, relative humidity, air velocity, and ambient temperature) were manually recorded at 30-minute intervals. During the experiment, the weather was generally sunny and no rain appeared. The important parameters affecting the performance of the insulator were measured. The K-type thermocouple was used to measure the dry air temperature at four points on the solar tunnel dryer (inlet, middle of collector,). The pyranometer (Solar meter model LI1400) was used to measure the global radiation Amou et al., 2013 [20]. The relative humidity and temperature of the ambient air were measured with a digital thermometer and relative humidity meter (ALMEMO-2250). The air velocity was measured with an anemometer (Taylor 3132) at the outlet of the collector. During the experiment, the weight of the product (maize) was measured using a digital precision balance (OHAUS-MB25 model) with an accuracy of 0.1 grams and a maximum measurement capacity of 100kg.

## 2.3. Numerical Setup

A schematic diagram of energy transfers inside the solar tunnel dryer is shown in the solar collector and the drying collector in figure 2 and figure 3 respectively, the following heat and mass balances are formulated.

### 2.3.1. Mathematical Modelling

The present thermal modelling work was inspired by the work of Agbossou & al. [26].

A thermal model to assess the thermal performance of a tunnel dryer was developed. The following assumptions were made while developing the thermal model:

- There is no stratification of the air inside the tunnel dryer,
- The products to be dried are assimilated into gray bodies,
- The temperature and moisture content of the product are assumed to be uniform,
- The different media are at a uniform temperature in a plane perpendicular to the airflow,
- The flow is identical throughout the crossing of the greenhouse, that is to say, that remains laminar, transient, or turbulent and does not change by regime,
- Drying computation is based on a thin-layer drying model,
- The specific heat of air, cover, and product is constant,
- The absorptivity of air is negligible,
- Radiative heat transfers from the floor to the cover and from the floor to the product are negligible.
- The airflow in the dryer is laminar and unidirectional,

A schematic diagram of heat transfers of the solar tunnel dryer and the energy flows through different components of the dryer is shown in figure 2.

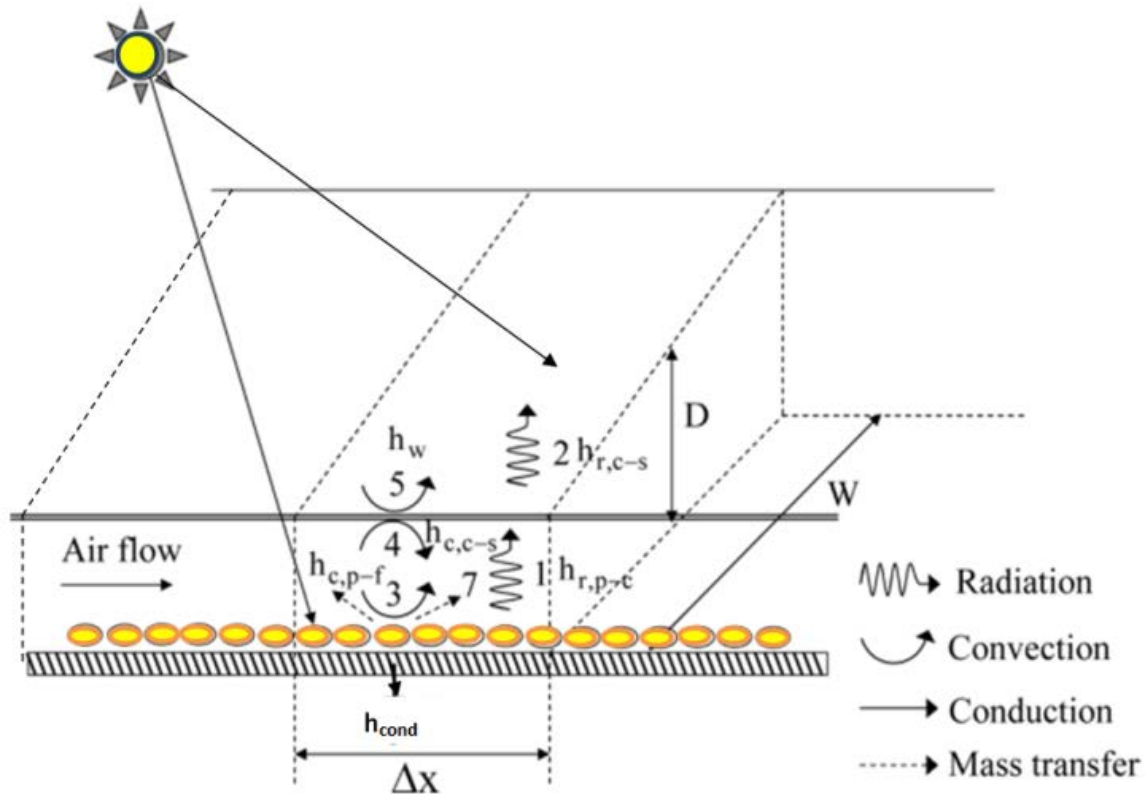


Figure 3. Different energy balance in the drying unit

### 2.3.2. Energy Balances

Energy balances on the different parts of the dryer are considered as follows:

$$m_i C p_i \left( \frac{\partial T_i}{\partial t} + \vec{v}_i \cdot \vec{\text{grad}} T_i \right) = \sum_i h x_{ij} S_{ij} (T_j - T_i) + \sigma_i \quad (1)$$

#### • Energy Balance of the Cover

The tunnel is covered with a UV-stabilized low-density plastic sheet. Solar radiation falling on the cover is allowed to be transmitted inside the tunnel. Energy balances on the tunnel cover are considered as follows: *Tapez une équation ici.*

$$\begin{aligned} m_c C_{pc} \left( \frac{\partial T_c}{\partial t} \right) &= S_c h_{c,c-a} (T_a - T_c) \\ &+ S_c h_{r,c-s} (T_s - T_c) + S_c h_w (T_{\text{amb}} - T_c) \\ &+ S_p h_{r,p-c} (T_p - T_c) + S_c \propto_c I_s \end{aligned} \quad (2)$$

The rate of thermal energy accumulated in the cover is:

$$Q_{th-cover} = m_c C_{pc} \left( \frac{\partial T_c}{\partial t} \right) \quad (3)$$

The convective heat transfer between air inside the tunnel and cover is:

$$Q_{c,c-c} = S_c h_{c,c-a} (T_a - T_c) \quad (4)$$

The radiative heat transfers between the sky and the cover due to radiation is:

$$Q_{r,c-s} = S_c h_{r,c-s} (T_s - T_c) \quad (5)$$

The convective heat transfers between cover and ambient air is:

$$Q_{c,c-w} = S_c h_w (T_{\text{amb}} - T_c) \quad (6)$$

The radiative heat transfers between the product and the cover is:

$$Q_{r,pr-c} = S_p h_{r,p-c} (T_p - T_c) \quad (7)$$

The solar radiation absorbed by the cover is:

$$Q_{s,c} = S_c \propto_c I_s \quad (8)$$

#### • Energy Balance of Air Inside the Tunnel

The air inside the tunnel dryer gets heated because of convective heat transfer among the floor, product, and air. The energy balances for the same can be written as follows:

$$\begin{aligned} m_{FC} C p_{FC} \left( \frac{\partial T_{FC}}{\partial t} + V \cdot \frac{\partial T_{FC}}{\partial x} \right) &= S_p h_{c,p-FC} (T_p - T_{FC}) \\ &+ S_c h_{c,c-FC} (T_c - T_{FC}) + S_f h_{c,f-FC} (T_f - T_{FC}) \end{aligned} \quad (9)$$

Thermal energy accumulation in the air (fluid colporteur) inside the tunnel dryer is:

$$Q_{th-FC} = m_{FC} C p_{FC} \left( \frac{\partial T_{FC}}{\partial t} + V \cdot \frac{\partial T_{FC}}{\partial x} \right) \quad (10)$$

The convective heat transfer between product and air is:

$$Q_{c,p-FC} = S_p h_{c,p-FC} (T_p - T_{FC}) \quad (11)$$

The convective heat transfer between floor and air is:

$$Q_{c,f-FC} = S_f h_{c,f-FC} (T_f - T_{FC}) \quad (12)$$

The convective heat transfer between cover and air is:

$$Q_{c,c-FC} = S_c h_{c,c-FC} (T_c - T_{FC}) \quad (13)$$

#### • Energy Balance of the Product

Convective and radiative are major heat transfer modes while balancing the energy of the product inside the tunnel. The energy balances energy for the same can be written as follows:

The thermal energy accumulation in the product = convective heat transfers between product and air + radiative heat transfers between product and cover + thermal energy lost from the product due to sensible and latent heat transfer + thermal energy gains by the product.

The energy balance on the product gives:

$$\begin{aligned} m_p C p_p \frac{\partial T_p}{\partial t} &= h_{c,a-p} S_p (T_a - T_p) \\ &+ h_{r,p-c} S_p (T_c - T_p) \\ &+ h_{r,p-f} S_p (T_f - T_p) - L_v \left( \frac{\partial M}{\partial t} \right) + \varphi \tau_c S_p \propto_p \end{aligned} \quad (14)$$

#### • Energy Balance of the concret floor

$$\begin{aligned} m_f C p_f \frac{\partial T_f}{\partial t} &= h_{c,a-f} S_f (T_a - T_f) \\ &+ h_{r,c-f} S_p (T_c - T_f) + h_{r,p-f} S_p (T_p - T_f) \\ &+ S_f h_{\text{conv}} (T_a - T_f) + \varphi \tau_c S_f \propto_f \end{aligned} \quad (15)$$

The overall heat loss from the air inside the dryer to ambient

$$Q_{c,am} = S_f h_{\text{conv}} (T_f - T_{\text{am}}) \quad (16)$$

#### • Mass Balance Equation

The air temperature inside the tunnel dryer is higher than the corresponding ambient temperature. It increases the ability to pick up moisture from the product, and the product gets dried. The rate of moisture accumulation in the air inside the tunnel dryer = moisture inflow into the dryer due to entry of ambient air + moisture outflow with exit air from the tunnel dryer + moisture removed from the product inside the dryer.

$$\begin{aligned} \rho_{FC} V \frac{\partial H}{\partial t} &= \rho_{FC} H_{in} V_{in} - \rho_{FC} H_{out} V_{out} \\ &+ S_p D_p S_p \frac{\partial M_p}{\partial t} \end{aligned} \quad (17)$$

The rate of moisture accumulation in the air inside tunnel dryer is:

$$M_{in-FC} = \rho_{FC} V \frac{\partial H}{\partial t} \quad (18)$$

The moisture inflow into the dryer due to the entry of ambient air is:

$$M_{\text{inflow}} = \rho_{\text{FC}} H_{\text{in}} V_{\text{in}} \quad (19)$$

The moisture outflow with exit air from the tunnel dryer is:

$$M_{\text{outflow}} = \rho_{\text{FC}} H_{\text{out}} V_{\text{out}} \quad (20)$$

The moisture removed from the product inside the dryer is:

$$M_{\text{remov}} = S_p D_p S_p \frac{\partial M_p}{\partial t} \quad (21)$$

#### • Thin-Layer Drying Equation

The thin-layer drying equation developed by Agbossou & al. [26] for drying maize under Hohenheim-type dryer similar to tunnel dryer was used to estimate the moisture ratio as Midlik model is:

$$\frac{X_t}{X_0} = a * \exp \exp(-kt^n) + bt \quad (22)$$

Where  $a$  and  $b$  were conducted experimentally in a solar tunnel dryer under variable conditions of temperature and relative humidity and the following thin layer drying equation was developed for thin layer drying of treated yellow corn by Gökhan.

#### • Heat transfer and heat loss coefficients

The convective coefficient taking into account the effect of wind on the outer wall is given by [18] in the form of equation (23)

$$h_w = 5,67 + 3,86V_w \quad (23)$$

Where  $V_w$  is the wind velocity ( $\text{m.s}^{-1}$ ), wind density is written by equation (24)

$$\rho = \rho_0.273 / (T + 273) \quad (24)$$

With  $\rho_0$  density at temperature  $T = 0^\circ\text{C}$ .

The convection heat transfer coefficients between the working fluid inside the annulus formed by the delivery plate and the absorber plate and the outside surface of the delivery plate and absorber plate are calculated by Kays et al. (2012) [14] from equation (25).

$$h_{c,a-pr} = h_{c,f-FC} = h_{c,c-a} = \frac{N_u \lambda_{\text{Flude}}}{D_H} \quad (25)$$

Where  $N_u$  is Nusselt number

The Nusselt number in the delivery plate surface for laminar flow ( $500 < \text{Re} < 7000$ ) is calculated Dissa and al., 2011, Duffie and Beckman, 2013 [12,15,16] by using Eq. (26)

$$Nu = 0,69 * \text{Re}^{0,514} * \text{Pr}^{1/3} \quad (26)$$

For turbulent flow ( $\text{Re} > 7000$ ) in the annulus and delivery tube, the Nusselt number is calculated by the Dittus-Boelter equation (Kalogirou, 2013; Incropera, 2011) [28, 29].

$$N_u = 0,036 \text{Re}^{0,75} \text{Pr}^{0,33} \quad (27)$$

Where  $\text{Re}$  is the Reynolds number which is given by:

$$\text{Re} = \frac{D_h * V_a}{\nu} \quad (27)$$

Where  $V_a$  air is speed in the insulator and  $\nu$  is kinematic viscosity of air.

The balance thermal coefficients by conduction throw collector to insulation can be calculated by the correlations below.

Radiation heat transfer coefficients between the plastic film cover and the sky can be calculated by the correlations below (Intawee, P, 2011; Daguenet Michel, 1985) [21,24],

$$h_{r,c-s} = \sigma * \varepsilon_{\text{Fext}} * (T_c + T_s) * (T_c^2 + T_s^2) * \frac{1 + \cos \beta}{2} \quad (28)$$

Where  $T_c$  is the sky temperature given below [16]

$$T_c = 0,0522 T_{\text{am}}^{0,5} \quad (29)$$

Radiation heat transfer coefficients between the absorber plate and the plastic film cover surface can be calculated by the correlations below (Eberlein, 1976) [30],

$$h_{r,p-c} = \frac{\sigma * (T_c + T_p) * (T_c^2 + T_p^2)}{\left(\frac{1}{\varepsilon_c}\right) + 1 + \left(\frac{1}{\varepsilon_p}\right)} \quad (30)$$

The overall heat loss coefficient from the tunnel floor ( $h_{\text{cond}}$ ) is computed from the following relation:

$$h_{\text{cond}} = \frac{k_f}{e_f} \quad (31)$$

#### 2.3.3. Software Description

The system of Eqs. (1; 2; 9; 14; 15) was solved numerically using the finite difference technique. The time interval should be small enough for the air conditions to be constant, but for the economy of computing, a compromise between the computing time and accuracy must be considered. Based on the drying air temperature and relative humidity inside the tunnel, the drying parameters  $a$ ,  $b$ , and  $k$  were calculated from Eq. (22) and the equilibrium moisture content ( $M_e$ ) of the Maize is computed using the thin layer equation of Midili [26,27] with  $a$ ,  $b$ ,  $k$  and  $M_e$  values. The change in moisture content of the Maize  $\Delta M$  for a time interval,  $\Delta t$  is calculated using Eq. (17). Next, the system of equations consisting of Eqs. (1), (2), (9), (14) and (15) are expressed in the following form for the interval  $\Delta t$ .

FRORTAN PGI 2008 was used for computing the unknown of Eqs. (1), (2), (9), (14) and (15). The input values of data were read from Origins using FORTRAN; the values were then written back to the same Origins file. The flow chart of the solution is illustrated in the following Figures.

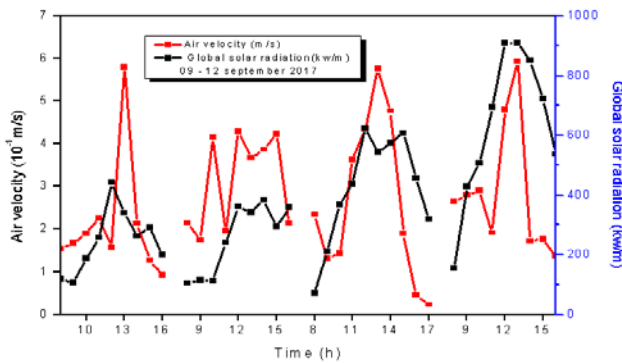
The model predictions were evaluated using the root mean square difference (RMSD) calculated from Eq.32.

$$\text{RMSD} = \sqrt{\frac{\sum_{i=0}^N (y_{\text{pre},i} - y_{\text{meas},i})^2}{N}} \times 100 \quad (32)$$

### 3. Results and Discussion

#### 3.1. Experimental Results

The tests of the loading solar tunnel dryer for drying maize were conducted during August and September 2017. The experimental results for drying Maize are shown in figures 4 to 7.

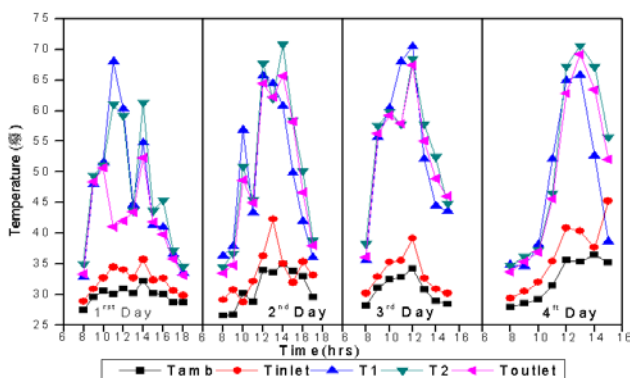


**Figure 4.** Variation of airflow and solar radiation with the time of the day during drying of yellow maize

Figure 4 shows the variation of airflow and solar radiation with the time of the day during the drying of yellow maize in the solar tunnel dryer. During the drying of maize, solar radiation increased sharply from 8 a.m. to noon but it considerably decreased in the afternoon. There was also a slight random fluctuation in solar radiation. However, the overall cyclic patterns of the solar radiation were similar except for the fourth day of solar drying of maize due to rain and the sky variation. The maximum solar intensity recorded was about  $900 \text{ w/m}^2$  during peak sunshine hours.

The airflow rate increases with time in the early part of the day and then it decreases with time in the afternoon. Moreover, the pattern of changes in airflow rate follows the pattern of changes in solar radiation. The maximum and minimum air velocities recorded were  $0.1 \text{ m/s}$  and  $0.6 \text{ m/s}$ .

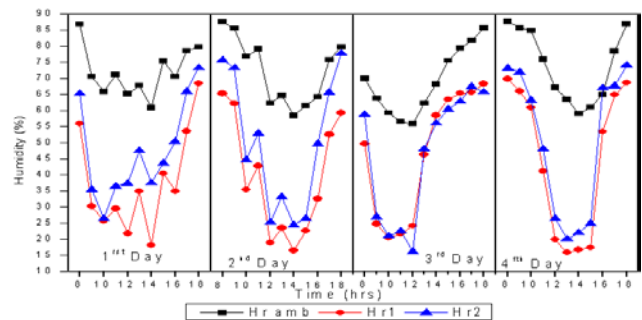
Figure 5 shows the profile of the temperature measured at the different points of the sensor. The variations of different temperatures are similar to that of the variation of solar irradiation. We note that the ambient temperature varied between  $24^\circ\text{C}$  -  $33.5^\circ\text{C}$ .



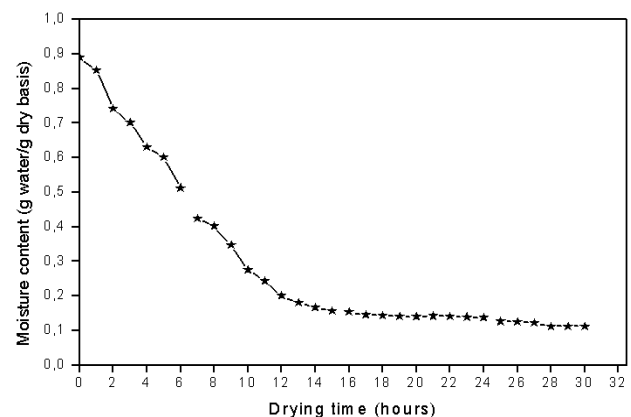
**Figure 5.** Variations of ambient temperature and the temperatures at different positions inside the Solar tunnel dryer for a typical experimental run during drying of dehydrated yellow maize

The drying air temperature at the collector inlet varies from  $28^\circ\text{C}$  to  $43.5^\circ\text{C}$ , and the drying air temperature at the outlet of the insulator varies from  $38^\circ\text{C}$  to  $68.5^\circ\text{C}$ . This indicates that the materials used for the absorber and insulation do not store heat. The drying chamber in this tunnel dryer required the maximum temperature for drying agricultural products in tropical areas.

Figure 6 shows relative humidity inside the dryers for typical experimental runs during solar drying of yellow maize. Relative humidity decreases with time inside the dryer during the first half of the day. This is caused by decreasing relative humidity of the ambient air and increased water holding capacity of the drying air due to temperature increase, whereas the opposite is true for the latter half of the day.



**Figure 6.** Variations of ambient relative humidity and relative humidity inside the solar tunnel dryer with time of the day for a typical experimental run during the drying of dehydrated yellow maize



**Figure 7.** Changes in moisture content with time intervals during in drying tunnel solar dryer

The relative humidity of the air inside the dryers is always lower than that of the ambient air and the lowest relative humidity is in the middle of the day which persists for about 5 hours. Thus, the time of day with the most potential for solar drying is between 8:00 and 16:00. Furthermore, the air leaving the dryer has lower relative humidity than that of the ambient air, which indicates the exhaust air from the dryer, still has drying potential. During the experimental drying, the average of the minimum relative humidity recorded in the inlet, middle, and outlet, of the solar tunnel dryer was 20%, 22%, and 30% respectively and the average of the minimum relative humidity for the ambient is 50%.

Changes in moisture content with time interval during in drying tunnel solar dryer has been shown in Figure 7.

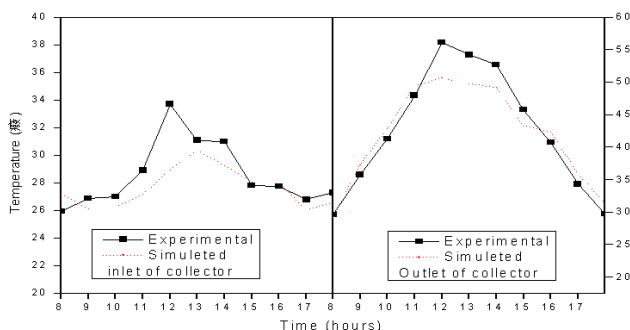
Inside the tunnel, the temperature was low in the first days when the temperature raised gradually until 2:00 p.m. and remained higher compared to the outside temperature, and that higher temperature accelerated drying performance. It was revealed that the moisture content of the maize declined very slowly during the first two hours of driving. Then the moisture content declined rapidly until the last four to seven hours which is a phenomenon related to the fact that when the moisture content of the maize was high, the air temperature decreased along the tunnel dryer, and due to the evaporative cooling on the surface of the products, the air temperature in the dryer dropped, resulting in reduced drying rate. A similar result was also reported by Muhammed and al. and Janjai, S., et al. (2009). using a sideloading type solar tunnel dryer [22,23]; The same result has reported by K.B. Uddin using Hohenheim type solar tunnel dryer in Bangladesh [25].

### 3.1. Simulated Results

The model was validated when the predicted air temperature at the different parties of the tunnel dryer and the moisture contents of the yellow maize during the drying were compared to the experimental values.

#### 3.1.1. Drying Air Temperature

Figure 8 shows typical comparisons between the predicted and experimental temperature values for the solar drying of maize. The predicted temperature shows plausible behavior and the agreement between the predicted and observed values is good.



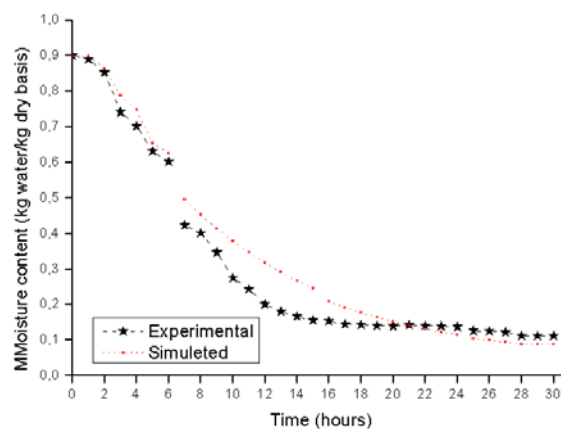
**Figure 8.** Comparison of the simulation and observer inlet and dry air temperature during drying of yellow maize

The inside air temperature plays a major role in removing moisture from a wet product. The drying chamber air temperature should be higher than the ambient air temperature. The maximum dry air temperature attained during the experiment was around 58.11°C. The difference between predicted and experimental results shows that this mathematical model can be used to describe and optimize drying kinetics under these climatical conditions.

#### 3.1.2. Moisture contents

Figure 9 shows comparisons of the predicted and observed moisture contents of drying maize inside the dryer. The model predicts well the moisture content changes of drying maize during drying. The model predictions for drying maize were evaluated based on root mean square difference (RMSD). RMSD of the prediction of the temperatures inside the dryer was 3.4%. This study

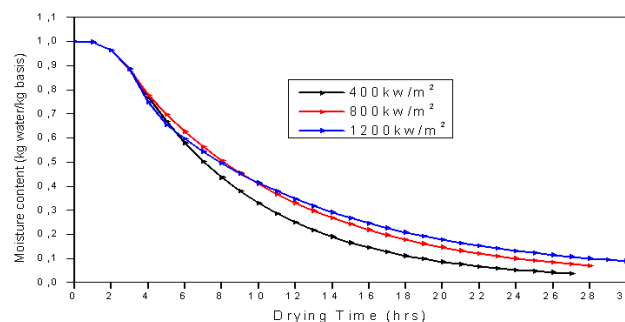
indicates that the model can predict the temperatures with reasonable accuracy. RMSD of the predictions of moisture contents of osmotically dehydrated tomatoes was 7%. Thus, the model predictions are reasonably accurate. Furthermore, predictions are also within the acceptable limit (10%).



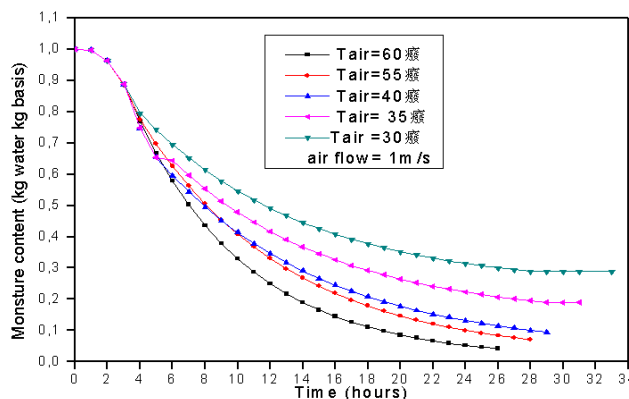
**Figure 9.** variation of the moisture content of maize with drying time

Figure 10 illustrates the influence of the intensity of daily solar radiation on its moisture content. It shows that during the drying time, solar radiation was very important.

To study the influence of solar radiation on the drying speed of corn, we take three months of solar radiation with different averages and we fix the average of the other parameters ( $H_r$ ,  $T_{ae}$ ,  $U_i$ ). It can be concluded that when the intensity of solar radiation increases, the drying time decreases.



**Figure 10.** The influence of solar radiation on the drying speed of corn



**Figure 11.** variation of the moisture content of maize with drying time for different dry air temperature

Figure 11 illustrates the influence of the dry air temperatures on its moisture content. The results confirm that the drying of the products is affected by the dry air temperature. It shows

that during the drying, the moisture content of 60°C of air drying temperature is more important for drying in a solar tunnel than the dry air temperature of 30°C. Increasing the air drying temperature reduces the moisture content.

## 4. Conclusion

A tunnel solar dryer has been constructed and imported by Hohenheim University. It was tested in Gape Kpodzi city (6°42'N latitude and 1°21'W longitude), in South Togo, 88Km from Lomé, during the summer season of 2017 to prove its potential for drying agricultural products under tropical climatical conditions. The theoretical and experimental study of solar tunnel dryer type Hohenheim allowed, first, the dry air temperature of the different parts of the dryer, second, it allowed the determination of the parameters that influence the drying kinetics for drying maize under tropical climatic conditions. As for factors that influence the drying kinetic, we can notice the dry air drying temperature and solar radiation. A mathematical model has been developed, this model allowed the evolution of the temperature at the different parts of the solar tunnel dryer. So a good agreement between the mathematical and experimental results was achieved.

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## Nomenclature

$S$  Exchange surface ( $m^2$ )  
 $S_1$  Surface area of solar collector ( $m^2$ )  
 $S_2$  Area of drying cabin ( $m^2$ )  
 $A$  Surface area of the solar panel ( $m^2$ )  
 $C_p$  Specific heat of the fluid (J/Kg. K)  
 $L_v$  Latent heat of vaporization (J/Kg)  
 $Hr_1$  Radiation coefficient between the cover and the celestial vault ( $W/m^2 \cdot K$ )  
 $Hr_2$  Radiation coefficient between the cover and the absorber ( $W/m^2 \cdot K$ )  
 $Hr_3$  Radiation coefficient between the absorber and the cover ( $W/m^2 \cdot K$ )  
 $Hcv_1$  Coefficient of heat transfer by convection between the cover and the ambient environment ( $W/m^2 \cdot K$ )  
 $Hcv_2$  Coefficient of heat transfer by convection between the blanket and the heat transfer fluid ( $W/m^2 \cdot K$ )  
 $Hcv_3$  Coefficient of heat transfer by convection between the absorber and the heat transfer fluid ( $W/m^2 \cdot K$ )  
 $Hcv_4$  Coefficient of heat transfer by convection between the insulation and the ambient environment ( $W/m^2 \cdot K$ )  
 $H_{cd}$  Coefficient of heat transfer by conduction between the absorber and the insulator ( $W/m^2 \cdot K$ )  
 $P_u$  Power of the heat transfer fluid ( $W/m^2$ )  
 $P$  Power per unit area ( $W/m^2$ )  
 $H_a$  Absolute air humidity (Kg/kg)

$U$  Overall loss coefficient  
 $D$  Diffusion coefficient ( $m^2/s$ )  
 $m$  Mass (Kg)  
 $D_m$  Air mass flow (Kg/s)  
 $Dh$  Water diameter (m)  
 $E$  Insulation thickness (m)  
 $F$  Cover form factor  
 $L$  Cabin length (m)  
 $L_c$  Sensor length  
 $H$  Sensor height  
 $Gr$  Grashof number  
 $Nu$  Nusselt number  
 $Re$  Reynolds number  
 $Pr$  Prandtl number  
 $P$  Pressure (Pa)  
 $PV$  Photovoltaic  
 $Q$  Radiated solar flux density ( $W \cdot m^{-2}$ )  
 $Q_0$  Solar flux density ( $W \cdot m^{-2}$ )  
 $A$  Product surface (m)  
 $DV$  Air volume flow ( $m^3/s$ )  
 $t$  Time (s)  
 $T$  Temperature ( $^{\circ}C$  or K)  
 $T_c$  Temperature of the celestial vault ( $^{\circ}C$  or K)  
 $V_w$  Wind Speed  
 $V_f$  Speed of the heat transfer fluid ( $ms^{-1}$ )  
 $X_R$  Reduced water content  
 $X_t$  Instantaneous water content  
 $X_i$  Initial water content  
 $X_{cr}$  Critical water content  
 $X_{eq}$  Equilibrium water content

## Greek Letters

$\alpha$  Absorptivity coefficient  
 $\beta$  Thermal expansion coefficient  
 $\Phi$  Thermal flow (Energies J)  
 $\tau_i$  Inflation rate  
 $\Psi$  Dimensionless current function  
 $\psi$  Dimensional current function  
 $\theta$  Dimensionless temperature  
 $\tau$  Transmission coefficient (radiation)  
 $\varepsilon$  Emissivity coefficient  
 $\sigma$  Stefan-Boltzmann constant ( $5.67 \cdot 10^{-8} W \cdot m^{-2} \cdot K^{-4}$ )  
 $\mu$  Dynamic viscosity of air ( $kg \cdot m^{-1} \cdot s^{-1}$ )  
 $\nu$  Kinematic viscosity of air ( $m^2 \cdot s^{-1}$ )  
 $\rho$  Air density ( $kg \cdot m^{-3}$ )  
 $\lambda$  Thermal conductivity coefficient ( $W \cdot m^{-1} \cdot ^{\circ}C^{-1}$ )  
 $\eta_t$  Instantaneous thermal efficiency  
 $\eta$  Average thermal efficiency

## Clues

iso Thermal insulation  
 op optical  
 pv Photovoltaic  
 v Cover (plastic film)  
 f Heat transfer fluid  
 amb Ambient  
 c sky  
 cab Cabin  
 p product  
 vast Saturated steam  
 w wind  
 e Entrance  
 s Output

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