Scientific Paper

Use of SolidWorks for the design of a solar dryer of pasture and forage botanical seeds

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Abstract

Objective: To utilize the computer system *SolidWorks* for the design of indirect forced convection solar dryers.

Materials and Methods: The computer system *SolidWorks* (version 2018) was used for the design of indirect forced convection solar dryers. The theoretical-methodological bases concerning the mechanical design and kinetics of heat transference were considered.

Results: The stated theoretical fundamentals allowed to establish the bases for the design of solar dryers of botanical seeds from pastures and forages. With the utilization of the above-mentioned computer system the technology was designed, and with the tool *Flow Simulation* the analysis of fluid kinetics and temperatures was carried out. Wind velocity values of 0,25 m/s and higher temperatures than the ambient temperature inside the drying chamber were reached. With the tool a study by finite elements was conducted to evaluate the structural resistance of the prototype through von Mises maximum stress. The resistance and stability of the prototype structure were proven.

Conclusions: The kinetic model, conceived with the utilization of the software *SolidWorks*, shows increase of temperature and fall of pressure in the solar dryer designed for drying botanical seeds from pastures and forages.

Keywords: natural drying, seed, thermal transference

Introduction

Since ancient times, farmers have developed sun drying for the conservation of foodstuffs, botanical seeds and agricultural crops. Yet, this method has some limitations, among which are great losses after harvest, caused by inadequate drying, fungi attack, invasion of insects, birds and rodents, unexpected rain and other meteorological events. In studies conducted by Andrejko and Grochowicz (2006) and Altuntas and Yildiz (2007) it was proven that the physical properties are influenced, to a large extent, the moisture content and the method for its extraction, aspect that indicates the need to reduce efficiently the moisture content.

The above-described limitations cause minimum quality standards. Artificial drying has proven to be more efficient than other procedures that do not allow to control the process integrally. This method guarantees higher conservation of the raw material to be processed and allows to reduce operation times, which influences the productivity of the process (García-Valladares *et al*., 2019) food security and to decouple food prices from the fluctuating prices of finite fossil fuels have driven the search for sustainable processing and the adequate storage of agricultural products. For this reason, a hybrid thermo-solar monitoring plant for the dehydration of foods was successfully designed and built in Zacatecas, Mexico. The thermal energy is provided by a solar air heating system with 48 collectors (111.1 m2.

In spite of the numerous studies conducted about solar drying technologies, aimed mainly at processing sea algae (Roche-Delgado *et al*., 2017), seeds (Collazo-Abreu *et al*., 2018; Morejón-Mesa *et al*., 2018), agricultural products (Teixeira-da-Silva and Malpica-Pérez, 2016; Ertekin and Firat, 2015), medicinal plants (Fonseca-Fonseca *et al*., 2019), biomass (Sonthikun *et al*., 2016) and greenhouses (Prakash and Kumar, 2017), the situation remains with little changes regarding the available solar dryers.

The use of this technology constitutes an economic alternative for small and medium farmers, because it allows them to improve their productive capacities (Carvallo and Meza, 2013).

According to the form of heat transference, solar drying technologies are classified into direct, indirect and hybrid solar dryers. According to the way in which solar energy is used and according to air circulation, there are natural or forced circulation systems (Roche-Delgado *et al*., 2017).

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The models of this type of technology are developed according to farmers' needs, production volume, availability of connection to the electrical grid, harvest seasonality and drying conditions of the products. They are basically active indirect solar drying systems, in which the products do not receive direct sunlight, and work through forced convection. In general, they have a solar collector of air, a drying chamber and a ventilator or extractor (Espinoza, 2016).

The objective of this study consisted in utilizing the computer system *SolidWorks* for the design of indirect forced convection solar dryers.

Materials and Methods

For designing the drying chamber the aspects that are explained below were taken into consideration.

Selection of the facility geometry, method of product support and air flow, depending on the product to be processed:

a. Three geometries (horizontal, inclined and conical), mainly, are considered, because they are the most widely used in the drying chambers of fixed-bed dryers.
b. Three methods of product support are assumed (fixed trays, mobile trays, fixed bed).
c. The product density is taken into consideration.
c. The recommended air flow and the size of the product bed for a certain load are given attention.

The simulation of the air performance inside the drying chamber using the program SolidWorks 2018 for the obtained geometry takes into account:

a. 2D and 3D
b. Constant temperature and rate in the outlet
c. Isolated drying chamber
d. Constant properties of air
e. The product as porous medium

The performance of the velocity field inside the drying chamber in 2D is analyzed and the velocities obtained are evaluated to verify whether the air is uniformly distributed in the product bed.

For conducting the study of the computational fluid dynamics (CFD) the following steps were followed:

- Resolution process through CFD
- 3D model
- Definition of the problem type, fluid type and frontier conditions
- Definition and generation of the mesh
- Establishment of the calculation parameters
- Calculation
- Obtainment and analysis of the results

Considerations for the design of the drying chamber. For obtaining the sizes of the drying chamber the following parameters are considered:

- Capacity of the product bed

$$\boldsymbol{V} = \frac{\boldsymbol{m}}{\boldsymbol{\rho}} \quad \text{where,} \qquad (1)$$

V: volume, m^3
m: product mass, kg
ρ: volumetric density, kg/m^3

- Height of the product bed (Faroni *et al*., 1993)

$$\boldsymbol{h} = \frac{6}{5} \cdot \sqrt{\frac{A}{\pi}} \quad \text{where,} \qquad (2)$$

h: height of the product bed, m
A: area of the transversal section, m^2

Regarding the air flow inside a fixed-bed drying chamber, several authors recommend a flow between 0,12 and 0,25 $\frac{m^3}{s}/m^2$, where m^3/s represents the air flow and m^2 the area of the transversal section (Faroni *et al*., 1993).

The outlet of humid air must be allowed and thus water condensation is prevented.

Temperature and air flow should be homogeneously distributed.

The design should be easily constructed, ergonomic and resistant, with materials that minimize heat losses.

The adequate selection of the materials that will be part of the prototype is fundamental for its correct functioning and durability in time. For such purpose, the criteria that are shown in table 1 should be considered.

For the determination of the area of the collector, it should be considered that it is directly proportional to the energy demand to perform the dehydration process, and that it is inversely proportional to the incident solar radiation and to efficiency. Equation 3 allows to establish the required area of the collector (Montero *et al*., 2010).

$$\boldsymbol{A_c} = \frac{Q_u}{I \times n} \qquad (3)$$

$$\boldsymbol{Q_u} = \boldsymbol{m_a} \cdot \boldsymbol{c_{pa}}(\boldsymbol{T_2} \cdot \boldsymbol{T_1}) \quad \text{where,} \qquad (4)$$

Ac: Area of the collector, m^2
Qu: Useful heat, kW
I: Global solar radiation (5 kWh/m^2 day)
n: Efficiency (80 %)

The most favorable placing of the solar radiation capturing surfaces will be that which, depending on the application at which the system is aimed, captures the highest possible quantity of energy. For the dimensioning of the capturers of photo-thermal systems, it is stated that the ideal way is to incline them on the horizontal, the latitude of the site plus 10 º. Thus,

Table 1. Selection criteria of the materials.

Criterion	Description
Resistance	Capacity of the material to stand flexion, compression or cutting failures.
Cost	Cost of the material acquisition
Resistance to corrosion	Capacity of the material to stand corrosion, without additives
Availability	Offer of the material in the national market
Conductivity coefficient	Resistance to heat conduction
Solar radiation absorption coefficient	Capacity of the material to absorb solar radiation
Capacity to reflect solar radiation	Capacity of the material to reflect solar radiation
Installation	Facility to install the material in the equipment
Durability	Capacity of the material to maintain its properties

the maximum yield is obtained in winter (Ekechukwu and Norton, 1999).

$\boldsymbol{\beta} = (\emptyset - \boldsymbol{\delta})$ (5), where the declination angle is given by:

$\boldsymbol{\delta} = \mathbf{23,45} \cdot \mathbf{sin}\left(\mathbf{360}\,\frac{\mathbf{284}+n}{\mathbf{365}}\right)$ (6) where,

β: inclination angle
L: latitude of the site

Considering that Cuba is located in the North hemisphere with regards to Ecuador, the collector surface should be oriented towards South. Thus, through the expression for the winter season (β=|Ø |+10°) it is determined that the optimum inclination angle between the surface of the collector and the horizontal should be of 32º, from the geographical latitude of the Institute of Animal Science (ICA, for its initials in Spanish), which has a value of 22º.

For the design of the drying chamber it is necessary to establish the conditions of its external structure, where the seed is deposited on a fixed bed. Initially, the volume of the seed to be processed is determined. Equation (7) allows to establish the volume of the drying chamber.

$V_{tp} = \frac{m}{\rho_{ap}}$ where,

Vtp: Total volume of the product to be processed, m^3
m: Total mass of the product to be processed, kg
ρ_{ap}: Apparent density of the product to be processed, kg/m^3

The relation between the area of the transversal section and height of the product (Faroni *et al.*, 1993) is determined by:

$$h = \frac{6}{5}\sqrt{A/\pi} \qquad (8)$$

The area of the transversal section of the drying chamber should have the following ratio (FAO, 1996):

$$L = 1.5\ a. \qquad (9)$$

With regards to the air flow inside a fixed-bed drying chamber, FAO recommends a flow between 0,12 and 0,25 m^3/s m^2 (Dalpasquale *et al.*, 1991).

In order to prevent crushing and consider an adequate space between the trays, the volume of the internal chamber is 0,054 m^3. The sizes of the internal chamber of the drying chamber are 0,52 m of width, 0,315 m of height and 0,33 m of depth.

Results and Discussion

For the design of the drying chamber of the solar dryer prototype aimed at the processing of botanical seeds of pastures and forages, the data obtained by Rojas-Barahona (2010) for the seed of *Mucuna deeringiana* were considered, and a physical-mechanical characterization of the seed was made for different moisture contents (table 2).

The volume and sizes of the drying chamber were defined through equation 7. For its sizes, the weight (W) of 200 kgf, and specific weight of the seed () of 1 000 kg/m^3, with 22 % moisture, were considered. Thus, a volume of 0,20 m^3 is obtained.

For the determination of the fluid movement kinetics (hot air) and the thermal performance inside the dryer and the seed layer, the incident solar radiation on the system or thermal facility was considered as initial datum, for which it was necessary to determine the optimum location of the solar collector in such facility, in order to obtain the highest possible thermal efficiency.

Taking into account the considerations and proposed methodology, the following results were obtained:

The meshing of the computational dominion and the frontier conditions applied to the model are shown in figure 1, where the mesh refining carried out can be observed. From a refinement level equal to 3 a total of 32 684 was obtained. From them 12 426 correspond to the fluid, 6 248 to the solid and 14 010 to partial cells, of solid and fluid.

The volumetric air flow that moves the electrical air extractor (activated by a photovoltaic panel) was made to intersect upon the outlet of the dryer

Table 2. Physical-mechanical characterization of the *M. deeringiana* seed.

Variable		Moisture, %			
		10	14	18	22
Sizes, mm	Length	16,29	16,52	16,76	17,21
	Width	10,68	10,82	11,02	11,28
	Thickness	6,94	6,98	7,18	7,41
Mean diameters, mm	Arithmetic	11,31	11,44	11,65	11,97
	Geometrical	10,65	10,76	10,98	11,28
Mass, g/1 000 seeds		909,04	969,85	1006,92	1035,55
Apparent density	ρa, g/cm^3	1,32	1,31	1,3	1,29
Real density	ρb, g/cm^3	0,88	0,87	0,85	0,82
Porosity	ε, %	33,03	33,6	34,51	36,19
Resting angle		16,9	17,37	21,28	22,09

Source: Adapted from Rojas-Barahona (2010)

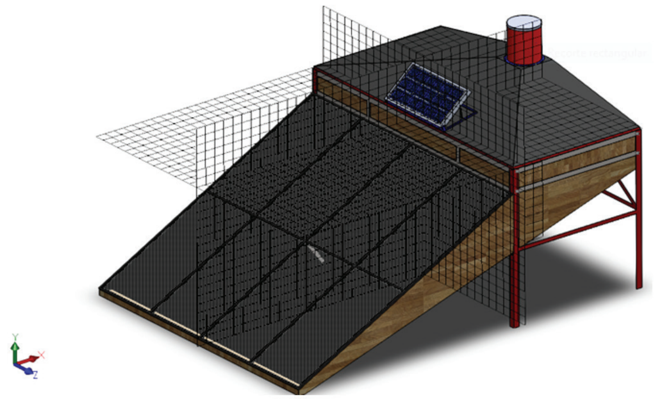

Figure 1. Frontier and meshing conditions of the computational dominion.

(red arrows) in normal direction to the X-Z plane, with value equal to 5 m s^{-1}. At the entrance total pressure is declared, having as reference atmospheric pressure (green arrows). In the simulation of the prototype the components declared as porous medium and perforated mesh were deactivated.

Through simulation a total of 333 iterations were obtained, performed to solve the convergence criterion for the engineering goals declared in the computer system, in a time of 1051 s. In the results a satisfactory convergence level was obtained.

Figure 2 shows the distribution of temperatures inside the dryer for a transversal cut in the Y-Z plane. Homogeneous temperature was achieved in the section of the drying chamber, which exceeded the ambient temperature by 12 ºC, with average temperature of 32 ºC. This favors seed drying, because the temperature did not surpass 45 ºC, recommended value for seed drying.

When analyzing the performance of relative pressure (figure 3), in the specific case of the variant that considers the porous medium, it could be observed that the minimum pressures were reached in the region of the extractor, specifically in the outlet, with value of -72,70 Pa. The maximum pressures were reached in the zone of the drying chamber, specifically in the solar collector, with a value of -0,48 Pa, which shows a pressure fall of 72,22 Pa.

Figures 4 and 5 (variant that does not consider the porous medium), the minimum pressures were reached equally in the extractor region, specifically at the outlet, with value of -48,23 Pa. The maximum pressures were obtained in the region of the drying chamber and the collector, with a value of -0,58 Pa, which showed a pressure fall of 47,56 Pa.

Simulations were made for the analysis of the prototype with the meteorological data of the last 12 months previous to the study (table 3).

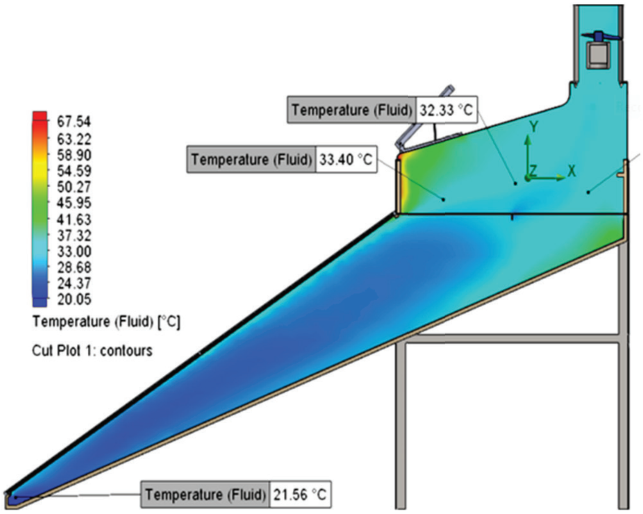

Figure 2. Distribution of temperatures inside the dryer.

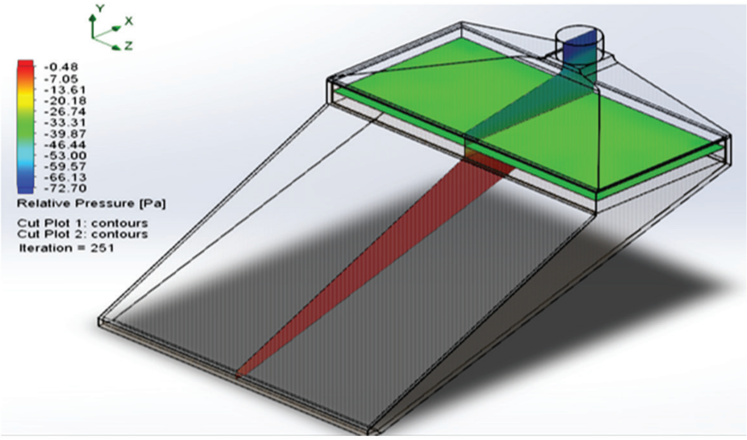

Figure 3. Performance of relative pressure (the seed layer is considered).

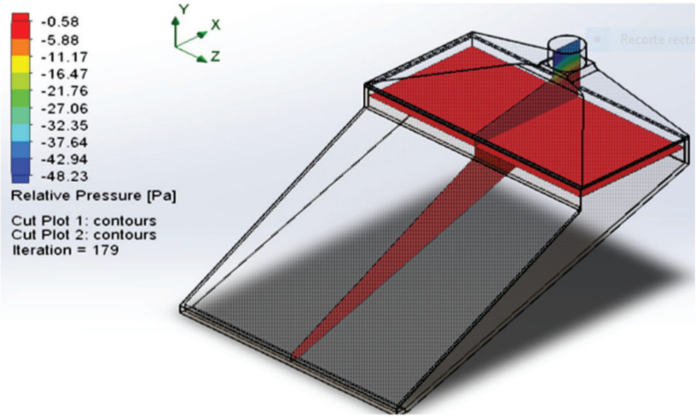

Figure 4. Performance of relative pressure (without considering the seed layer).

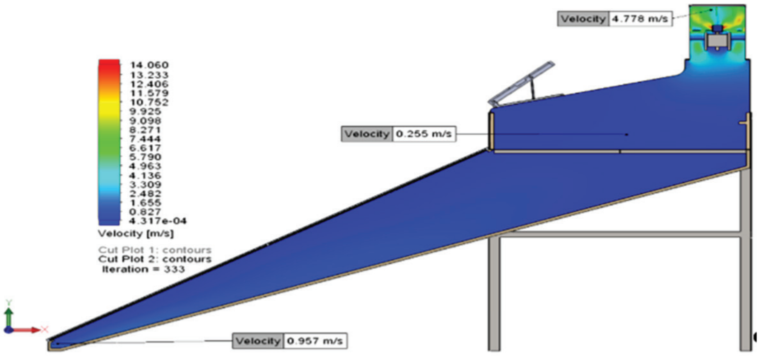

Figure 5. Performance of relative pressure (without considering the seed layer).

Table 3. Data of monthly ambient and internal temperature of the dryer.

Year	Month	T_{min}	T_{max}	RH, %	T_{max} without MP	T_{max} with MP	T_{med} seed bed
2018	September	24	31	78	40,27	46,23	32,79
	October	22	30	78	39,47	44,49	30,89
	November	20	28	75	37,28	41,74	28,76
	December	18	27	74	34,92	39,65	26,71
2019	January	18	26	75	35,06	39,29	26,49
	February	18	26	73	35,5	40,01	27,1
	March	19	28	71	35,79	41,41	27,02
	April	20	29	71	36,51	42,13	28,77
	May	21	30	74	37,62	44,01	28,96
	June	23	31	76	41,11	44,59	30,79
	July	24	32	75	43,6	44,35	31,61
	August	24	32	76	43,3	45,06	32,25

The meteorological variables mean minimum temperature and relative humidity for each month were considered (INSMET, 2019).

In the simulations performed the variables of maximum temperature within the dryer were determined, taking into consideration the seed bed (T_{max} with MP) or not (T_{max} without MP), besides the mean temperature in the seed bed (T_{med}) (table 3).

With the annual meteorological variables of Cuba a simulation was carried out of the functioning of the solar dryer for each month of the year, according to the above-described resolution method through CFD. In total 24 simulation studies were conducted, where for each month of the year the performance of temperatures inside the dryer was analyzed, considering and not considering the seed volume. The simulations showed that the months in which the highest temperatures were reached in the designed prototype, without including the seed layer in the simulation, were July and August, with values of 43 ºC as maximum temperature. For the analysis of maximum temperatures, when considering the seed volume, the months that reached the highest temperatures inside the dryer were August and September, with maximum of 45 ºC and 46 ºC, respectively.

When conducting the analysis of the fluid that circulates through the seed volume in the drying chamber, it could be noted that during August and September temperatures of 32 ºC were reached, respectively, and increase of 8 ºC was achieved with regards to the ambient temperature fixed in the CFD analysis. For the months of lower mean minimum temperature (December, January, February) temperature increase similar to the warmest months was achieved, with increase of up to 9 ºC.

In general, after analyzing the performance of temperatures inside the designed prototype, it is valid to emphasize that the mean temperature obtained in the seed bed did not exceed 32,79 ºC, for which it was found below the recommended temperature for seed drying. This should not exceed

40 ºC. This limit value has been validated by several authors, among which Andy (1970) and Humphreys (1976) can be cited, who state that the temperatures for safe drying are related to the initial moisture content. The general recommendations for field crops are 32, 37 and 40 ºC, for moisture contents of 18 and 10 % to 18 %, and less than 10 %. In studies conducted by Silcock (1971) it was proven that for temperatures higher than 40 ºC, low viability was reached during storage.

Another result was the simulation of the performance of the temperatures reached by the materials of the component parts of the prototype and fluid temperature inside the dryer in general, and of the drying chamber in particular for eight hours of work (table 4). This simulation was carried out for ambient conditions of minimum temperature of 17 ºC, average air relative humidity of 70 % and solar radiation of 4,2 kW. These average values constitute ones of the lowest that could exist during the summer months, in which it would be more complex to achieve an increase of temperatures in a solar dryer.

As shown by table 4, the maximum temperatures achieved in the prototype materials reached 91,07 ºC at 12 h, and had as average 83,24 ºC. The highest values were obtained between 10 and 14 h. Something similar occurred with the performance of the fluid temperature in the drying chamber, the maximum as well as the mean. The highest values were obtained at 12 h, which coincides with the time of highest temperature of the solids, with values of 61,64 and 27,50 respectively. Likewise, it could be corroborated that the temperature inside the drying chamber was higher between 10 and 14 h, for an average of 27,25 ºC and a daily average for the fluid temperature of 25,93 ºC, being 8,93 ºC higher than the ambient temperature. The highest temperature values were reached at solar noon, when solar radiation has its most perpendicular incidence on the capturing surface.

Conclusions

The kinetic model, conceived through the utilization of the program *SolidWork*s, proved an increase of temperature and a pressure fall inside the solar dryer designed for drying pasture and forage botanical seeds, specifically for *M. deeringiana* seeds.

For unfavorable conditions of solar radiation and low temperatures during the simulation of the fluid kinetics, the designed prototype reached temperatures that exceeded the ambient temperature by 8,0 ºC. In the seed bed, the mean temperature did not exceed 32,8 ºC, for which it is below the recommended one for seed drying, which should not surpass 40,0 ºC, maximum recommended for guaranteeing the conservation of the physical, chemical and reproductive properties of seeds.

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Authors' contribution

- Yanoy Morejón-Mesa: Conception of the proposed design, analysis and interpretation of the results, formulation of the objective, establishment of the work methods and elaboration of the document.

Table 4. Performance of the temperatures of the solids and fluid in eight hours of work.

Time	$T_{initial}$	Temperature of solids,		Temperature of fluid,	
		T_{max}	T_{min}	T_{max}	$T_{drying\ chamber}$
8		71,25	15,30	34,26	22,86
9		80,42	18,97	46,08	25,26
10		86,74	20,78	56,95	27,16
11		90,56	22,43	59,20	27,49
12	17	91,07	23,51	61,64	27,50
13		90,06	22,21	58,81	27,17
14		87,37	21,30	57,80	26,94
15		80,41	19,41	45,66	25,45
16		71,24	17,28	36,81	23,50
Average		83,24	20,13	50,80	25,93

- Yoel Rodríguez-Gago: Conception of the proposed design, interpretation of the obtained results, document writing and revision.
- Darielis Vizcay Villafranca: Interpretation of the results, document writing and revision.

Conflict of interests

The authors declare that there is no conflict of interests among them.

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