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Design of a Hybrid Dryer for Hemp Flowers for the Inter-Andean Region of Ecuador

J. Peralta-Jaramillo[1], E. Delgado-Plaza [1], A. Rivera [1], D. Rivera [1], C. Polanco [1], J. Reinoso[1], Ian Sosa-Tinoco[2], X Álvarez-Montero[3]

[1]*ESPOL Polytechnic University, Escuela Superior Politécnica del Litoral*, Centro de Desarrollo Tecnológico Sustentable, Facultad de Ingeniería en Mecánica y Ciencias de la Producción, Guayaquil, Ecuador, email–: jperal@espol.edu.ec, eadelgad@espol.edu.ec, *alcrrive@espo l.edu.ec*, *darivera@espol.edu.ec, chranpol@espol.edu.ec, josirein@espol.edu.ec*
[2]Electrical Engineering Department, Instituto Tecnológico de Sonora, Mexico email: –ian.sosa@itson.edu.mx
[3]Vicerrectorado de Investigación y Vinculación, Universidad Estatal de Bolívar, Campus Laguacoto
Guaranda Km. 1 1/2 vía San Simón, Guaranda-Ecuador, e-mail: xalvarez@ueb.edu.ec

Abstract. The hemp flower has gained relevance in the agro-industrial and medical field worldwide due to the analgesic, anti-inflammatory, and antiepileptic benefits that cannabidiol offers. A critical process in post-harvest is drying, as this allows to maintain the intrinsic properties of the flower. This operation requires a constant heat supply that involves high energy consumption. Therefore, a dryer was designed that uses a hybrid heat supply system based on solar thermal and electric energy. For this, a design of the chamber with a dome cover capable of taking advantage of solar radiation was made together with a system of collectors, supported by an electrical resist for periods of low irradiance. A theoretical analysis of the process was carried out considering the speed and temperature as study parameters and was validated by simulation and dynamic fluid modeling (CFD), obtaining that the thermal power to dry 120kg of the flower is 8.52kW, supplied by 4 solar collectors in series, the dome-type cover, and a tubular resistance of 2kW. The proposed design meets the requirements for maintaining a temperature of 50 ° C within the chamber during the drying time and a speed of 0.5m/s, which guarantees that the product is dehydrated without affecting its organoleptic properties and quality. Furthermore, the project will contribute as a benchmark for technological innovation in the use of renewable energy sources in Ecuador.

Keywords-- medicinal hemp, cannabidiol, solar thermal energy, dryer, hybrid systems.

1. Introduction

In recent years the cultivation and processing of hemp have spread for use in different fields, such as medicinal, cosmetic, production of textile fibers, food products among others. This increase in its world production is largely thanks to the new legislation that countries are considering concerning the agricultural management of this plant species. In practice, the data reveal that the cannabis industry grows at a rate of 30% per year and has doubled in recent years, "by 2025 it is expected to reach 145,000 million dollars [1] [2]. Within this context, Ecuador has approved the regulations that regulate the production and commercialization of industrial hemp, on October 19, 2020; which seeks to position it as one of the leading countries in the production of both raw materials and products derived from this plant [3] [4].

In medicine, products based on cannabidiol (CBD), the main component of the hemp flower, are used, "which is associated with analgesic, anti-inflammatory, and antiepileptic activities". [5]

However, an industrialized process is required, from the planting phase to the extraction phase of cannabinoids, and technological equipment for harvesting and processing hemp will be required in the emergence of this new industry. One of the mandatory pre-treatments is drying, this unitary operation is performed on the bio-product to "increase shelf life, reduce weight, packaging costs, improve appearance, encapsulate the original flavor and maintain nutritional value" [6]

In particular, the cultivation of hemp will allow the agro-industrial sector to promote the fulfillment of sustainable development goals. Objective 7, affordable and non-polluting energy: the use of clean energy sources will encourage growth and technological development, as well as help the environment. Goal 8, Decent work and economic growth: Sustainable economic growth will be stimulated by increasing levels of productivity and technological innovation by providing decent work for the men and women involved. Objective 9, industry innovation and infrastructure: the development of an inclusive and sustainable industry that can contribute to employment and GDP is possible. Objective 13, Climate action: development of plans in Ecuador for the use of systems or equipment with low environmental impact. To this end, the general objective of the project was established to design a dryer for hemp flowers that uses a hybrid energy system as an energy source, through the application of mathematical models and computational simulation, promoting the use of renewable energies in the post-harvest of hemp in Ecuador. [6] [7] Finally, in Ecuador, it is estimated that there are around 800 companies associated with the entire production chain [4], for which technological equipment will be required for harvesting and processing hemp. One of the mandatory pretreatments is drying, this unitary operation is carried out on the bio-product to "increase shelf-life, reduce weight, packaging costs, improve appearance, encapsulate the original flavor and maintain nutritional value", [8] in addition to developing a sustainable drying system that contributes to the local energy transition and contributes to the decarbonization of industrial processes and the use of renewable energy sources at the national level [9]

A. *Hemp parameters in the drying process*

Drying occurs when water is removed by supplying heat to the raw material [10]. One of the objectives of drying is to achieve the right percentage of humidity for the easy handling of the product, conservation, and reduction of transport costs, among others [11]. In addition, a high-water content promotes the development of microbial agents, which accelerate decomposition [12].

In practice, for the realization of drying, the following parameters are considered:

Maximum temperature

An important parameter in this process is temperature, values above 70 ° C promote degradation of the chemical composition of the flower [13].

Moisture content

Regardless of the initial humidity (depending on the variety of the plant, climatic conditions, and harvesting process), the final humidity should be between 10-13% [13], [14].

Drying curve.

The drying process can be quantified by measuring moisture loss over time, which is represented by a drying curve [15].

This curve is characterized by three distinctive stages; during the first one, the vaporization of surface moisture occurs, for which the drying rate is constant. The second consists of a decrease of this rate, while the water inside the solid is transported to the surface by diffusion and capillarity. For the third, the drying speed decreases further and is influenced by the thermal conduction within the solid until it reaches the equilibrium value for the humidity of the surrounding air, after which it stops [16]. Shown in Figure 1, the characteristic drying curve of the hemp flower reported by [13].

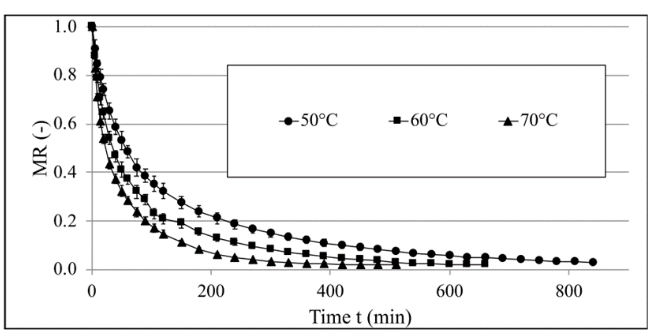

Fig. 1: Drying speed curve for hemp flower Henola variety, MR: Moisture Ratio

Environmental characteristics of the implementation area.

Cayambe is one of the outstanding cities in agriculture for the use of greenhouses for flower production for the national and international market, in addition, the soil complies with the required availability that allows the cultivation of this plant species. Regarding the monthly radiation of the place, there is a higher value in August and September with figures close to 190kWh / m^2. The monthly ambient temperature range (Figure 2) is between 3 and 23 °C, with an estimated average value of 12.4 °C.

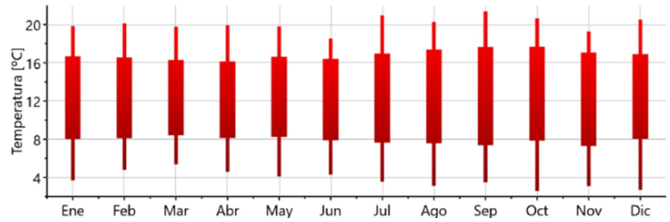

Fig. 2: Ambient temperature range in Cayambe

2. Methods

B. *Definition of requirements*

According to ministerial agreement 109, corresponding to the production and commercialization of hemp in Ecuador, the issuance of all types of licenses within the production chain involves a minimum production of 2 hectares for non-psychoactive hemp for medicinal use under greenhouse. [17] This made it possible to establish a maximum drying capacity of *120kg* per cycle.

The manipulation of the flower must be minimal at the time of drying because the terpenes containing cannabinoids are very fragile and can easily detach from the flower causing losses of these compounds, so a system that guarantees minimum manipulability of the product while it dries is vital to ensure its quality.

Finally, according to [13], the variables for the drying of hemp flower, which are considered as design requirements, are presented in Table 1.

Table 1 Fixed design requirements

Variables	Value
Air velocity [$\frac{m}{s}$]	0.5
Initial flower moisture [%]	68-80
Final humidity required [%]	10-15
Drying temperature [$^{\underline{o}}C$]	50

C. *Influencing Factors*

Certain decisive factors were established in the design of the drying system as presented.

• Stable flow: the flow distribution in the drying chamber is of great importance to obtain a uniform drying of the flower.

•Homogeneous temperature: maintaining the homogeneous drying temperature inside the drying chamber also influences the uniformity of the process and above all that the product entered does not suffer damage such as cracks or thermal stress.

• Total cost: this factor is very important since it determines whether it is feasible to commercialize it at the national level, which manages to compete with similar systems that must necessarily be imported.
• Local availability of materials: If manufacturing materials and manufacturing processes are available locally, it is possible to reduce costs and therefore increase their scalability and marketing.
• Safety and maintenance: The operation of the system should be considered safe and easy to operate for the operator, in addition to considering a design that allows easy access to all its components for proper maintenance.
• Hybridization of the energy source: The adaptability of an alternative system of power generation using nonconventional energy sources defines the type of dryer to be used. Some of them are easier to hybridize than others, so it is a parameter to consider. More than 70% of the cost over the lifetime of a convection dryer is due to energy consumption, so the selection of an energy-efficient system is essential [16].
• Size: the system must be compact to facilitate installation in any location, without limiting space.

D. Shape Design

From the analysis of process variables and product characteristics it was determined that the most suitable option for the hemp flower drying system under the given requirements, the tray dryer is the most suitable. The selected alternative consists of 3 equidistant inputs and one output, to obtain a better flow distribution that allows uniformity throughout the chamber for more efficient drying. Additionally, the cover was made of dome and polycarbonate type, to take advantage of the high irradiance of Cayambe.

Based on the requirement for the issuance of planting extension licenses mentioned above, the drying chamber was sized for a capacity of 120 kg of product per cycle, distributed 1 kg in each tray for a total of 8 shelves of 15 trays each as presented in Figure 3, having external dimensions of 1.9m*1.1m*2.05m.

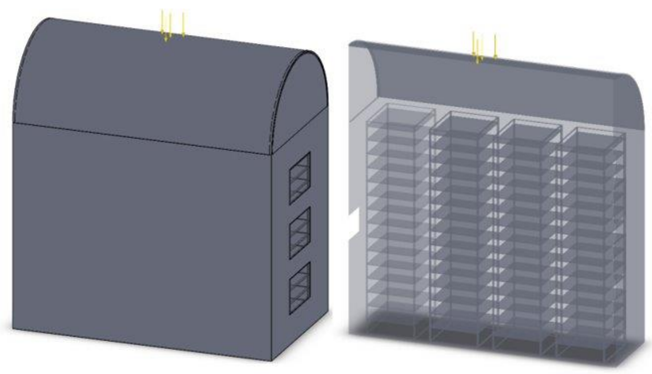

Fig. 3: Shape design of the drying chamber.

Additionally, the complete system was designed considering collectors in series for the heating of the air up to the required 50 °C, the centrifugal fan that provides the airflow, an auxiliary tubular resistance system for low irradiance stages and a control system to fix the airflow and the on and off of the electrical resistance, the general scheme of the system is presented in Figure 4.

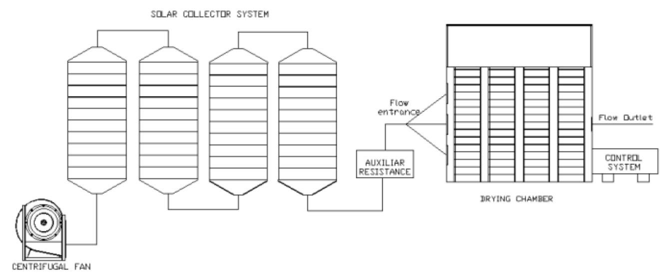

Fig. 4: Hybrid drying system.

3. Results

E. Mathematical Model

The initial process consisted of calculating the thermodynamic properties of the air by using the psychometric chart to determine the volumetric flow required for drying. The process from the input to the first collector to the exit of the chamber is presented in Figure 5.

From these data, mass of water to evaporate and the amount of water absorbed by the air, the required volumetric flow was determined.

$$\dot{V}_a = \dot{m}_a/\rho = \frac{0.19\ kg\ air}{s} \Big/ \frac{1.09\ kg}{m^3} = 0.17\ m^3/s \quad (1)$$

Also, the heat losses associated with convection and conduction were determined using equation 2.

$$U = 1 \Big/ \left({}^{1}/_{h_i} + \sum_{i=2}^{4} {}^{l_i}/_{k_i} + {}^{1}/_{h_o} \right) \quad (2)$$

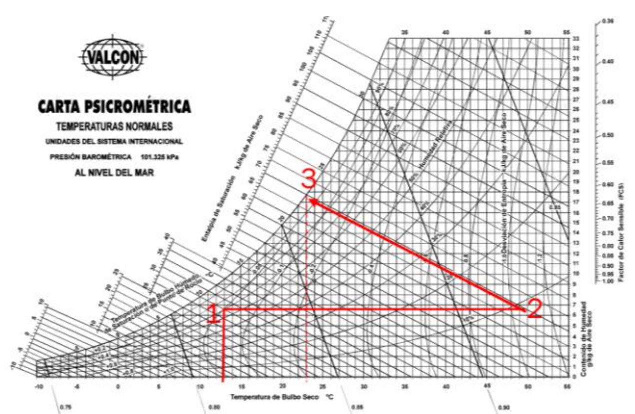

Fig. 5: Thermodynamic properties of air. [18]

Finally, the heat provided by radiation in the dome type cover was determined and the total heat required for the drying process was calculated using equations 3 and 4 respectively.

$$Q_{rad} = (A_{dome})(\alpha)(Gr) \quad (3)$$

Q_{rad}: *Heat contributed by solar radiation* $[W]$
A_{dome}: *Dome area* $[m^2]$
α: *Dome absorptance*

Gr: $mean\ irradiance\ [kWh/m^2d]$

$$Q_{req} = Q_{dryer} + Q_{losses,w} + Q_{losses,c} - Q_{rad} = 8.52kW \quad (4)$$

Q_{req}: $Net\ energy\ requirement\ [W]$
Q_{dryer}: $Drying\ heat\ [W]$
$Q_{losses,w}$: $Heat\ lost\ throught\ walls\ [W]$
$Q_{losses,c}$: $Heat\ Lost\ throught\ the\ roof\ [W]$

The mathematical model for the sizing of the solar collector system included the estimation of an initial area according to equation 5, to then recalculate the required heat, the average temperature of the plate that is the variable for the iterative process, and the output temperature of the collector, according to equations 6,7,8 respectively.

$$Ac = Qutil/[S - U_L(Tpm - Ta)] \quad (5)$$

$$Qu = Ac * Fr\left(S - U_L(Tfe - Ta)\right) \quad (6)$$

$$Tpm = Tfe + Qu/Ac/Fr * U_L\,(1 - F'') \quad (7)$$

$$To = Tfe + Qu/\dot{m}Cp \quad (8)$$

From this iterative process, a collector area of $4.33m^2$ was established which has 2.94m*1.47m.
All the previous calculations were done for a single collector, but for the complete system the calculation of the total heat and the final output temperature is required using equations 9 and 10. Based on this calculation and trying to meet the requirement of required heat and temperature, a maximum of 4 collectors were established in series to meet all the energy needs.

$$Q_{u,1} + Q_{u,2} = A_1F_{R1}[G_T(\tau\alpha)_1 - U_{L1}(T_i - T_a)] + A_2F_{R2}[G_T(\tau\alpha)_2 - U_{L2}(T_{o,1} - T_a)] \quad (9)$$

$$T_{o,1} = T_i + \dot{m}\frac{Q_{u,1}}{C_p} \quad (10)$$

The outlet temperature of each collector was calculated for different irradiances per hour established in the meteorological data of the area in the worst scenario of the year to have an adequate dimensioning for these conditions.

Finally, the auxiliary resistance system was selected since the previously selected and sized components depend on the solar resource of the area, therefore, there are many temperature variations in the drying process, which is not desirable, so an alternating system of electrical resistances was determined. From equation 11, the requirement of a tubular resistance of 2kW was established to supply the necessary heat energy when it was the case.

$$\dot{Q} = 1.1\dot{m}Cp\Delta T \quad (11)$$

F. System Simulation

Furthermore, to validate the design proposal, the temperature and speed values were determined at strategic points located inside the drying chamber (Table 2) by simulation using the Solid Works Flow Simulation tool [19] [20]; These results were compared with the requirements of 50 ° C and 0.5 m/s

.

Table 2. Coordinates of the points studied inside the chamber

z / x	Plano y=1.125 m			Plano y=0.75 m			Plano y=0.375 m		
	-0.475	0	0.475	-0.475	0	0.475	-0.475	0	0.475
0.275	1	2	3	10	11	12	19	20	21
0	4	5	6	13	14	15	22	23	24
-0.275	7	8	9	16	17	18	25	26	27

Once the solar collector was simulated with the appropriate input conditions, the output temperature values were checked with the one theoretically calculated from Equation 10, thus obtaining the comparative result of Figure 6.

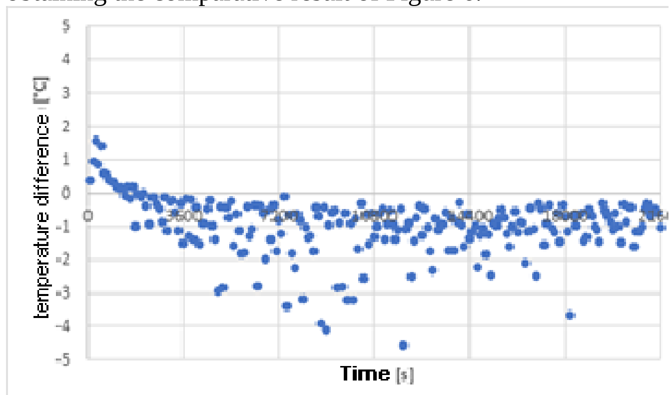

Fig. 6: Difference of the theoretical and simulated temperatures in the collector

Additionally, as a comparative measure, a sensitivity study was carried out on the solar collector that allows measuring the accuracy of the simulation; for this, the mean square error (RMSE) and bias (BIAS), commonly used statistics, were determined. Finally, the linear correlation coefficient between the theoretical values and the simulated values of the output temperature as presented in Figure 7 was studied.

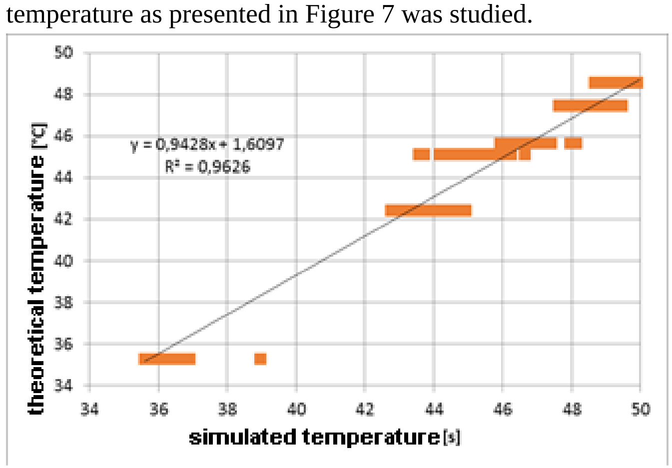

Fig. 7: Theoretical temperature vs the simulated temperature at the collector outlet.

In the case of the drying chamber as shown in Figure 8 the temperature distribution in the chamber is not completely uniform due to the presence of trays that cause a redistribution of flow and a change in speed; additionally, variations in irradiance on the dome throughout the day cause an increase in temperature at 1:00 pm (Figure 8) where the irradiance is a maximum, however, the temperature does not exceed 70 ° C to prevent damage to the flower.

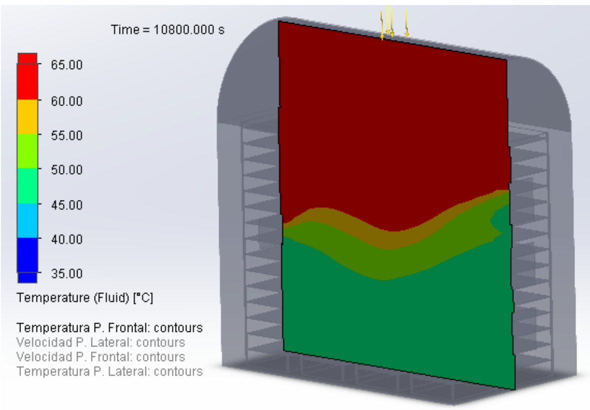

Fig. 8: Temperature distribution in the drying chamber (front view). at 1:00 P.M.

Globally, as observed in figure 9, the variation of the average temperature of the fluid during the six hours of drying is shown, for a temperature input of between 35 and 48 °C, coming from the solar collector; It is observed that during the first four hours a temperature close to 50 °C is maintained thanks to the greenhouse effect, while the last two hours the temperature drops to a final value of 35 °C, so it will be required to activate the electrical resistance system to meet the missing energy requirement.

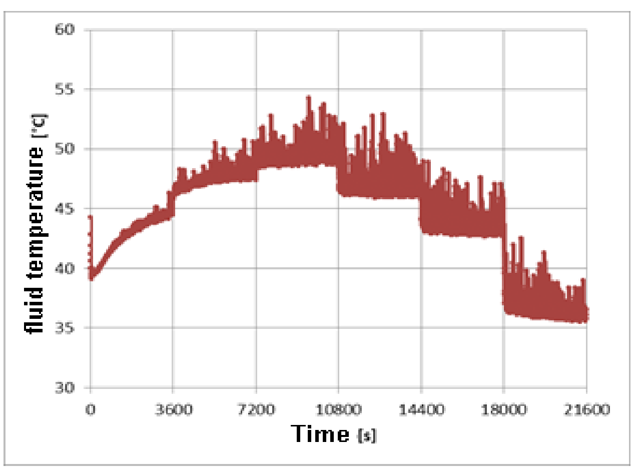

Fig. 9: Variation of the average air temperature with time.

Studying the behavior of speed is imperative to validate the proposed design, as mentioned, hemp needs to dry at no more than 0.5 m / s to prevent the detachment of terpenes, prevent the flower from burning superficially, and lose its organoleptic characteristics. Figure 10 shows that this requirement has been met.

The addition of trays to the chamber undoubtedly generates greater turbulence of the fluid inside as can be seen in Figure 11. The generation of obstacles to the flow is observed and therefore a more uniform distribution is achieved, which guarantees flow in each of the trays and therefore in each bud of the hemp flower.

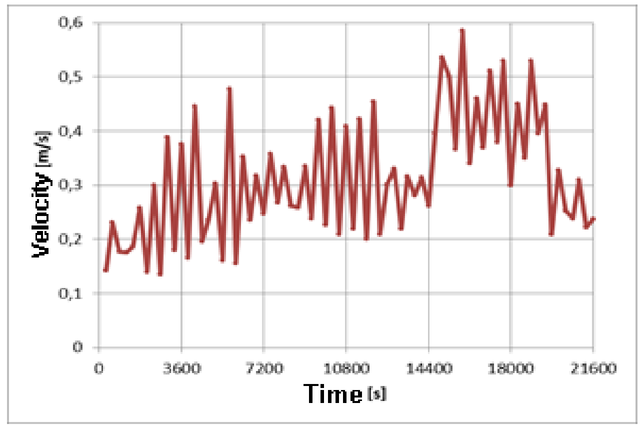

Fig. 10: Variation of the average air velocity with time.

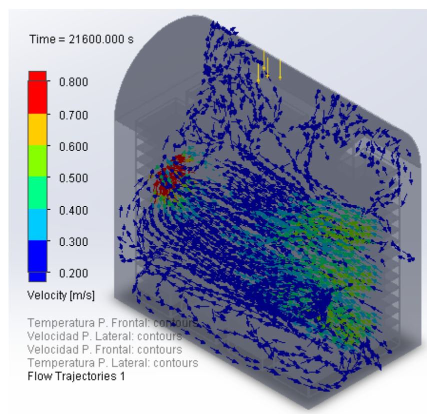

Fig. 11: Flowlines (speed) in the drying chamber.

G. Cost Analysis

Based on the selected design, a complete analysis is necessary that involves both the cost of materials for the dryer, the collector, auxiliary, and control energy systems and design cost, which also involves an analysis of amortization of the initial investment to validate the viability of the project.

Through national quotations, a total cost of the drying system with a hybrid energy source of approximately $12,670.00 was established, considering the additional cost per manufacturer that involves man-hour values.

The current international cost of dried hemp flowers in bulk is around $165.00-dollar American per pound [21]. The dryer designed in this project has a capacity of 120kg of wet flower, therefore, 85 pound of dried flower is obtained which is equivalent to $ 14 025.00 per lot. A profit margin of 30% per lot was considered [21]. The net margin would be $4207.5 per load. Finally, considering the net cost of the dryer and the profit margin, the payback period is expected to be a maximum of 4 lots of hemp production for the capacity of the aforementioned dryer; considering the entire scope of production, infrastructure, and additional machinery is already established.

4. Conclusions

From the mathematical model, it was possible to determine by energy analysis, that the amount of total heat required to dry 120 kg of hemp flower is 8.52 kW; which come from a hybrid energy system corresponding to four solar collectors in series, the dome type cover with a contribution of 2.16 kW due to the greenhouse effect and resistance with a capacity of 2000 W, complying with the stipulations about the use of renewable energy resources in the area.

Following this, from the study of the sensitivity of the model, it was possible to validate the temperature results at the exit of the solar collector system, using the calculation of the mean square error (RMSE), bias (BIAS), and the linear correlation coefficient.

The correlation coefficient obtained from 0.96 between theoretical and simulated data, allowed us to establish that there is a high relationship between the results calculated by energy analysis and the simulation results. In this way, it can be concluded that the computational model presented an underestimation of 1 ° C in a stable way, with a low RMSE value equal to 1.31 °C, which corroborates the accuracy of the model.

However, examining the simulation results obtained for the drying chamber, specifically, the stratified temperature analysis highlighted one of the weaknesses of the proposed design, is that due to the presence of trays there is a considerable variation of 19.3 ° C between the upper and lower levels of the point distribution shown in Table 3. However, the highest values corresponded only to the section of the dome but not to where the trays are distributed. Additionally, the highest temperature value is 54 ° C, which fulfills the requirement that the flower must be dried at less than 70 ° C to achieve the conservation of its organoleptic properties and chemical composition that guarantee the retention of terpenes and therefore the subsequent extraction of high amounts of CBD.

Thanks to the dome design, it was possible to increase the temperature of the fluid by approximately 17°C at 1:00 pm at the points adjacent to its surface, and that by convective effects it was possible to distribute to the lower levels of the chamber, which means a decrease in the energy requirement and therefore a reduction in costs. It was possible to validate the action of solar radiation on the roof due to the increase in temperature when the irradiance is maximum, at 1:00 p.m., and then this decreases in the last hours of operation.

Additionally, it is concluded that for irradiance values below 521W/m^2 it is required to activate, using a control system, the auxiliary resistance equipment that will provide a maximum of 23% of the energy requirement, since in these conditions the temperature inside the chamber has a value lower than 50 °C, which is not suitable for drying since it takes more s time the process of dehumidification and therefore greater energetic consumption.
From the study of the simulation of the solar collector regarding the speed distribution, it was observed that for an inlet flow equal to 0.17m^3/s, a speed was obtained in a range of 0.15 to 0.52 m/s inside the drying chamber, with a maximum value at point six located in the high plane of trays, at a height of 1,125m from the central entry position. Also, using these numerical results and Figure 11, which shows the current lines, it is concluded that the flow provided by the centrifugal fan from the inlet of the collectors to the exit of the chamber provides a non-uniform speed, however, the range is adequate for the optimal drying of all the buds in each of the trays. On the other hand, this analysis was carried out for a single collector, so it cannot be said that the volumetric flow requirement is the one specified, because in real life there are losses due to friction and accessories. However, in fan selection, the possibility of a greater flow requirement was considered, because it can provide up an additional 0.11 m^3/s additional to the current value.

In the three inputs of the chamber, the speed is higher, this is because the flow is not yet dispersed in a larger area, in the same way to the exit the fluid is accelerated since there is a Venturi effect due to the decrease of the cross-sectional area, causing an increase in speed and decrease in pressure.
Studying the range of values close to the input and output of the chamber, a weakness of the proposed design was identified, since the values range from 0.4 to 0.8 m / s, which means that the increase in speed in these areas could harm the product since the undesirable detachment of the terpenes could occur.

5. Discussion

In the present research work, a comparative study was not presented between the heat theoretically obtained with that calculated by the computational software, because an energy analysis was not carried out inside the chamber. After all, the thermal energy required for the drying process involves latent and sensitive heat, which implies introducing a model that represents the flower in the simulation environment with its main thermophysical properties such as humidity. and its porous structure, this results in a more complex analysis that comes out of the objectives of this research; in addition, there is an additional system of power generation by resistors that provides heat intermittently which does not allow an ideal comparison of results and would not generate reliable results that can be established as valid.

Therefore, the objective is met concerning the design of a drying system that uses a hybrid energy source, these being solar energy and electricity supply, taking advantage of the energetic renewable resources of the inter-Andean region of

Ecuador. Furthermore, by the results presented above, it was possible to validate the design by comparing the theoretical and simulation calculations of the variables of temperature and flowrate within the chamber.

In general, it can be inferred that the drying system designed for hemp flowers allows according to specifications and cost, to compete with tray drying equipment designed by American production companies since the net acquisition cost is 83.5% lower. From the above, it was possible to assess the feasibility of the construction of this project, through an economic analysis, availability of resources, and benefits not only for the industry but also for Ecuadorian society.

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