Simulation of a flat solar collector with thermal storage for drying food

Simulación de un colector solar plano con almacenamiento térmico para el secado de alimentos

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***Abstract*—This research addresses the numerical simulation of a working fluid, using specialized SolidWorks Flow Simulation Software, analyzing the behavior of a drying air in a flat solar collector with thermal energy storage. In addition, one of the main centers of computational study is the relationship between flow, air temperature at the outlet of the collector and efficiency; This study allows researchers a vision of the principles of the design of these technologies, especially if it focuses on the drying of food. Then, a proposal is made on the requirements to be taken into account for the sizing of collectors based on the requirements of the product to be dried. Among the results obtained, it is established that a correctly designed collector and under a variable air flow, based on the intensity of the irradiation in specific coordinates and location, can reach efficiencies close to 30% with temperatures close to 60 ° C, being ideal for injecting this fluid into a drying chamber, where the food to be dehydrated is available. For the selection of the volume of the material for energy storage, it is recommended to take the melting temperatures as a base, with a constant flow of air, it is normal that within the system, the temperature varies depending on the position, therefore it is recommending the application of materials with different melting temperatures, which are strategically located within the storage tank.**

***Index Terms*— drying; numerical fluid simulation; solar collector; solar energy; thermal energy storage.**

***Resumen*—Esta investigación aborda la simulación numérica de un fluido de trabajo, utilizando el software especializado SolidWorks Flow Simulation, analizando el comportamiento de un aire de secado en un colector solar plano con almacenamiento de energía térmica. Además, uno de los principales centros de estudio computacional es la relación entre caudal, temperatura del aire a la salida del colector y eficiencia; Este estudio permite a los investigadores una visión de los principios del diseño de estas tecnologías, especialmente si se enfoca en el secado de alimentos. A continuación, se hace una propuesta sobre los requisitos a tener en cuenta para el dimensionamiento de los colectores en función de los requisitos del producto a secar. Entre los resultados obtenidos, se establece que un colector correctamente diseñado y bajo un flujo de aire variable, en función de la intensidad de la irradiación en coordenadas y ubicación específicas, puede alcanzar eficiencias cercanas al 30% con temperaturas cercanas a los 60 ° C, siendo ideal para inyectar este fluido en una cámara de secado, donde se encuentra disponible el alimento a deshidratar. Para la selección del volumen del material para almacenamiento de energía, se recomienda tomar como base las temperaturas de fusión, con un flujo de aire constante, es normal que, dentro del sistema, la temperatura varíe dependiendo de la posición, por lo tanto, recomienda la aplicación de materiales con diferentes temperaturas de fusión, los cuales se encuentran estratégicamente ubicados dentro del tanque de almacenamiento.**

***Palabras claves*— almacenamiento de energía térmica; colector solar; energía solar; secado; simulación numérica de fluidos.**

I. Introduction

DRYING is an excellent agricultural activity to overcome spoilage problems in foods such as fruits, vegetables, and grains. Due to the high energy consumption, this process represents an important cost in the industry, because it is required for storage and transportation, it is estimated that this represents between 10-15% of the total industrial energy consumption [1]–[3].Additionally, the energy domain is experiencing an accelerated effort to find solutions to the current energy crisis, due to the excessive use of fossil fuels for thermal processes [4].

Renewable energy sources and energy storage are addressed as possible solutions. An example of this is the use of the sun in rural areas for drying food, which is naturally used by different farmers. Within a sustainable development for the efficient use of renewable energies, different types of solar collectors have been proposed to generate a drying control, reducing times and guaranteeing the quality of the product in each of the harvests.

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Leaving aside the dependence on atmospheric and environmental conditions [5]–[7].

When it comes to the development of drying systems in developing countries that take advantage of solar energy, the flat collector and the storage of thermal energy become an effective tool. Additionally, when an efficient use of solar radiation is applied through an absorbent metal plate and adequate insulation, improvements in drying times are reflected in research [8].

In this research, numerical computational simulation is used to address the analysis of the behavior of fluids, within a solar collector with latent thermal energy storage, in order to seek the highest efficiency, simulating a flow control and seeking to maintain values of temperature that contributes to quality drying [9].

II. Materials And Methods

The purpose of this research is focused on achieving a more complete understanding of the behavior of air heating systems using flat solar collectors, using thermal energy storage to improve stability in a real environment. When we talk about solar radiation, the condition of instability is present, due to the different environmental variables that can affect the power of the radiation that affects a certain point or place on earth. Variables such as inclination, position, time of day, atmospheric conditions, the ability of a material to absorb, reflect and transfer this energy, are issues that must be considered when designing a solar collector. Additionally, the application or energy requirement of the collector is essential when making decisions about its sizing [10]–[12].

To begin addressing the proposed research, a foray into databases is made, reading different scientific articles and books on food dryers. In this search, the classification of these is identified, whose main distinguishing characteristic is oriented to the form of use of solar energy. The systems that allow direct radiation from the sun to the product are called direct dryers; Those that use a solar collector to heat the air, which is directed to a chamber containing the product, is called indirect dryer and those that combine these two concepts are called mixed dryers. Additionally, when another source of energy is added to compensate for the instability of the sun, it can be defined as a hybrid dryer [13], [14].

Solar collectors are mainly composed of a metal plate with a special coating to improve the absorption capacity of solar energy, additionally they have a transparent cover or layer, which has the function of allowing the passage of solar rays so that they can impact on the absorbent plate and fulfill the role of thermally insulating the system so that heat is not transferred to the environment in an accelerated way. Under the conditions described above, a collector efficiently takes advantage of solar radiation to heat fluids such as water and air [15].

In order to make a simulation as close to reality, it is important to define characteristics, such as the collector material that defines its thermal resistance, solar radiation (power and direction or angle of incidence), air flow, among other specifications necessary for a correct execution of the Flow Simulation program. In order to identify the properties that are used in a flat solar collector, databases are approached in the search for scientific articles that present information on computational numerical simulations.

A. *Characteristics of the simulation of the manifold for drying*.

As previously stated, the project focuses on the design of a collector for drying cocoa or other agricultural products such as coffee. Based on the literature, these systems must reach temperatures close to 60 ° C to generate quality drying without damaging the organoleptic properties of the product.

For design purposes, four main components will be used, a wooden box which has the function of containing and structurally supporting the system. The wood with which the box is built has the advantage of thermally isolating the air to be heated to minimize heat losses and, due to its accessibility and economy, it becomes a suitable material for agricultural applications.

The second component is the absorbent metal plate which is applied a special coating to improve its ability to capture solar radiation and heat up over time, for the simulation it is defined as copper because it has appropriate heat transfer characteristics for the study. The third component is the transparent cover that allows the passage of solar radiation and is defined as glass, which is a material present in the program that facilitates the simulation of collectors.

The final component is the thermal energy storage material, the main subject of study for this project is the incorporation of heat storage, with the purpose of stabilizing drying temperatures taking into account the variability of solar radiation and prolonging times. Based on the bibliography, there are two types of materials for storing thermal energy: latent heat and sensible heat. When talking about latent heat, the phase change of the substance is explicit and for sensible heat the phase change is not achieved.

Within the literature it is highlighted that phase change materials have a greater capacity to store energy due to the fact that they absorb heat in large quantities during the phase change stage and release it efficiently when it returns to its original state.

In the databases there are different types of materials used for energy storage, but each of these must be used based on the specific requirements of the application, such as operating temperature, construction materials due to possible oxidations or chemical reactions, toxicity, costs, among others. Under these criteria different authors [16]–[18] point out the advantage of paraffin for drying applications due to its low cost, long useful life, its melting temperature below 60 °C and low toxicity. Due to its properties, it can have thousands of energy charge and discharge cycles without undergoing changes in its composition.

For the reasons described above, paraffin is selected for the investigation of the flat solar collector with thermal energy storage. Therefore, it is necessary to define its thermal properties to feed the simulation software database. A study that stands out for analyzing in detail the behavior of different paraffins is that carried out by [19], With his research he manages to define the properties with which the program is fed for the simulation. These data are tabulated as shown below (TABLE I).

For research terms, 60 ° C is defined as working temperature, which means that in operation a control system must approach this control point, for this reason a paraffin with a melting temperature close to this value, hardly it may change state in its entire volume, for this reason you should choose a paraffin whose melting temperature is less than 60 or at least 10 degrees. For the purposes of the development of the project, PW48 is selected because it is commercially accessible and has the necessary characteristics for the execution of the research.

TABLE I
SUMMARY OF THE THERMO-PHYSICAL PROPERTIES OF PW48 PARAFFIN

Thermo-physical properties	Value	
Density	780 $\left({kg}/{m^3}\right)$	
Dynamic viscosity	0.024 $(Pa * s)$	
Specific heat CP	2300 $\left({J}/{kg * K}\right)$	
Thermal conductivity	292.15 K	0.3 $\left({W}/{m * K}\right)$
	343.15 K	0.23 $\left({W}/{m * K}\right)$

B. Boundary Conditions.

By defining the different conditions through reading the different scientific articles mentioned above, it is possible to approach the SolidWorks CAD simulation software and its Flow Simulation application. To carry out the test, a 1 m2 collector is modeled under the following boundary conditions.

- Room temperature T_{amb} 20.5 °C.
- Initial temperature of the fluids (Air and paraffin) 20.5 °C.
- Solar irradiation of 500 - 1000 W/m^2 the angle of incidence (θ) at 0° to emphasize the thermal study of the collector
- Diameter of the collector air inlet 10 cm.
- The properties of reflection, absorption and thermal conductivity are applied under the predefined parameters in the software for materials such as wood, iron and glass.

The air velocity inside the collector is varied in m / s, in order to analyze the behavior of the system.

C. Circulation system proposals.

Correct air circulation is important for the design of a collector, in order to efficiently absorb solar radiation and transfer it to the fluid used in drying, with this premise in mind, a model is developed for a 2 m^2 (1m x 2m) collector, as seen below. Additionally, the absorption plate allows the transfer of thermal energy to the paraffin, storing energy during its phase change (see Fig. 1).

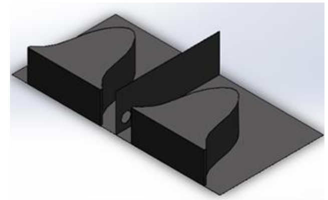
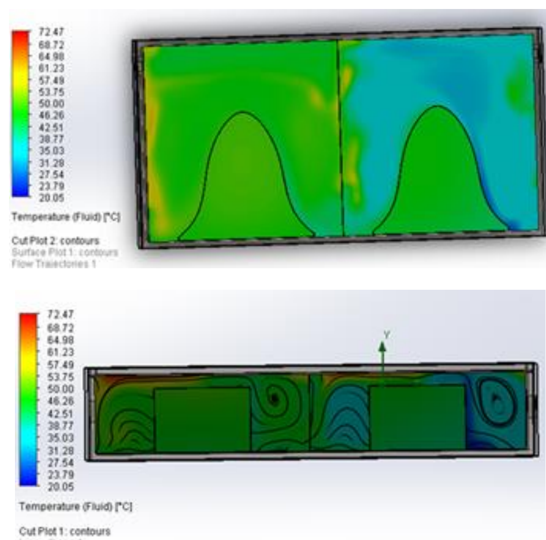


Fig. 1 Solar absorption plate with energy storage. The paraffin container tanks generate a forced movement of the air circulating inside the collector.

This plate is modeled with the aim of containing 2 stores for the paraffin, additionally two separate spaces are created with a through hole, as seen in the figure to generate a directed circulation within the collector. For the simulation, three air flow velocities are applied, one at 2 m/s, another at 1 m/s and the final one at 0.5 m/s. As can be seen in the following figure, the increase in temperature inside the collector is affected by the separation applied to the plate.

Bearing in mind the different aspects of radiation absorption and the area of heat transfer, a proposal is made for a solar collector for drying that allows the air to circulate efficiently through it. Additionally, it must also allow the heat transfer air to the paraffin to be comparable to that of the air, so that both fluids have access to solar energy. The proposed recirculation system with energy storage is shown in Fig. 2.



(a)

(b)

Fig. 2 Temperature of the fluids inside the collector, a) Top view, b) Side view.

It is also possible to appreciate the behavior of the air inside the collector, in which eddies are created, showing turbulence due to the air inlet and its speed [20]. The temperatures obtained are tabulated in TABLE II.

TABLE II
FLUID TEMPERATURE

Air inlet velocity $\left({m}/{s}\right)$	Outlet air temperature (°C)	Maximum paraffin temperature(°C)
2	38.48	44
1	42.17	49
0.5	48.31	51

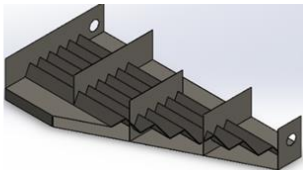
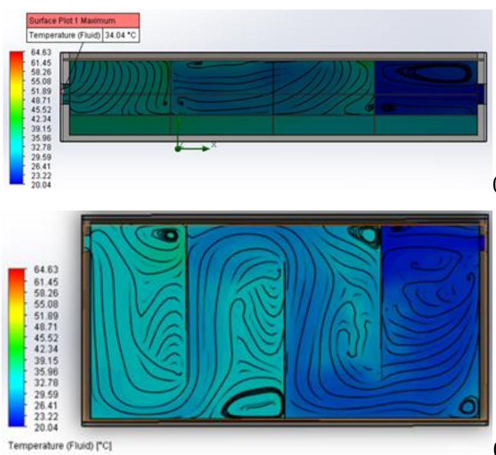


Fig. 3 Recirculation and energy storage proposal.

As can be seen, the radiation receptor consists of a lower chamber for storing the paraffin and dividing sheets are implemented that generate a forced air circulation (see Fig. 3). The pyramidal plates have the function of creating turbulence within the collector in order to improve heat transfer, in addition, by increasing the contact area between air and metal, it also contributes in this aspect [21].

With the simulation of this model, an air velocity of 3 m/s is applied in the first instance and the area of the circular inlet with a diameter of 10 cm is kept constant, to carry out a detailed analysis two additional velocities of 1 and 2 m/s. The irradiance is kept constant at 600 W/m^2, a value that serves as a comparative to define the efficiency of the collectors applied in the simulations.



(a)

(b)

Fig. 4 Temperature of the fluids inside the collector a) Side view, b) Top view.

In figs 3 and 4, it is possible to appreciate the heating of the air as it advances through the solar collector, the dividing plates that force the air to circulate along the path allow to show the path that the fluid follows, until reaching a temperature of 34 °C at the outlet. The paraffin for this case reaches a maximum temperature of 39 ° C, which shows that both fluids reach similar temperatures. Additionally, TABLE III shows the tabulated results of the speed and temperature of the working fluid (air), the maximum temperature reached by the paraffin and the approximate efficiency of the collector.

TABLE III
BEHAVIOR OF FLUIDS

Air inlet velocity $\left(m/_{s}\right)$	Outlet air temperature $(°C)$	Maximum paraffin temperature $(°C)$	Efficiency (%)
3	34.04	37	32.3
2	37.21	41	26.4
1	43.54	45	18

To obtain the efficiency of the collector , the equations found in the article of [22], are used, the first is to find the power of energy absorbed by the air by means (1):

$$Q = \dot{m} * C_p(\Delta T) \quad (1)$$

Where Q is the heat generated or absorbed, $\dot{m}$ is the mass flow of the air that can be found by the air velocity and the inlet area. C_p is the specific heat at constant pressure that is tabulated in the literature according to temperature and ΔT is the difference between the outlet and inlet temperatures, which, as defined from the beginning, is 20 °C. For efficiency (2) is used [23], [24].

$$\eta = \frac{Q_a}{Q_T} \quad (2)$$

Where η is the efficiency, Q_a is the heat absorbed by the air and Q_T is the heat of incidence on the collector obtained by multiplying the total area by the irradiation, which for this specific case would be 600 W/m^2 * 2 m^2 = 1200 W.

From the models discussed above (Figs 2 and 4) it is possible to begin to highlight notable similarities and differences. The first similarity is found in the temperatures and efficiencies achieved, the two collector proposals achieve very close values in the heat absorbed by the air as it passes through the system. This is mainly due to the length traveled by the air inside it, both collectors are divided into 4 sections, regardless of the shapes or curvatures that are applied inside the collector, what prevails is the length traveled by the air and the heat transfer area between the metal plate and the air.

The most notable difference is the temperature reached by the stored paraffin in the case of the model in fig 5, it reaches temperatures between 40 and 50 °C and in the previous model its temperature remains below 45 °C. It is important to be clear about what a stable state refers to, it is the point at which the system does not drastically vary the temperature of the fluid, for this specific case, air is used as a reference point, which means that when it reaches its stable state at the outlet of the collector, the simulation is stopped, so it is not clear what is the time required to reach the maximum temperatures of the paraffin and if this is the limit that it can reach.

For the purposes of these simulations it is possible to identify that the proposed models have an important difference and it is the total volume of the paraffin, for Fig 5, the volume of the paraffin is 0.078 m^3 and for fig 8 the volume is 0.26 m^3. In percentage relationships, the first model has 30% of the mass that the second has, which represents a considerable difference in thermal load. Due to the temperature relationships of the fluids, it is possible to point out that the efficiency for heating the air is not affected by the amount of paraffin, because in both cases the temperatures reached were very similar. The hypothesis raised with this analysis is that the amount of PCM (Phase Change Material) for energy storage affects only the heating times of the same and this does not affect the temperatures reached by the air, which do depend on the speed (Volumetric or mass flow) and the length by which it circulates inside the collector.

III. Results

The proposed collector design is based on the storage of thermal energy based on the reached temperature of the paraffin in each one of the analyzed conditions. The paraffin content is 0.6 m^3, uniformly distributed throughout the collector, the total area is 8 m^2 and the applied materials continue under the same boundary conditions that have been established in the previous simulations. Shown below is the metal plate of the manifold.

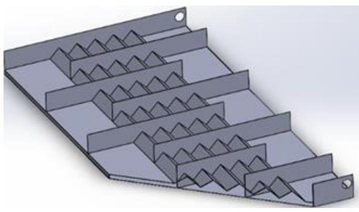


Fig. 5 Receiver plate (8 m^2).

The plate has 8 divisions or sections through which the air passes while it is heated, the solar radiation applied in the simulation is configured at 500 and 1000 W/m^2, with the aim of identifying the temperature under conditions of average or average radiation and high for midday hours when intensity is highest.

The results of the simulations for irradiation of 500 and 1000 W/m^2 are shown in TABLE IV, where the speed and temperature of the air, the temperature reached by the paraffin and the efficiency that the collector would reach are observed.

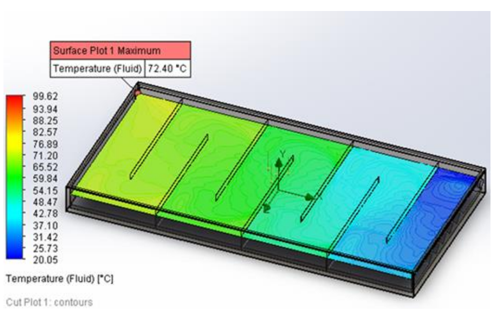


Fig. 6 Air temperature inside manifold 8 m^2.

As can be seen in Figs 6 and 7, with these conditions it is possible to exceed 60 °C and by applying correct air flow control, by maintaining the levels required for quality drying and energy efficiency. The different simulations carried out are tabulated to be analyzed precisely as shown below.

Table Iv
Summary Of Data Obtained In The Simulations

Air inlet velocity (m/s)	Outlet air temperature $(°C)$	Maximum paraffin temperature $(°C)$	Efficiency (%)
500 W/m^2			
1	57	52	8.5
3	49	47	20
5	43	43	26.58
1000 W/m^2			
3	72	71	17.95
5	64.6	66	25.66
7	59	62	31.41

It is necessary to have a context of the behavior of the air in the hours of maximum irradiation, this allows dimensioning the air flow requirements to keep the drying temperature below 60 °C. As can be seen from the simulations, in this collector it is possible to apply air flows between 1 m/s and 7 m/s and thus guarantee efficiency and temperature depending on the radiation present. But using temperature as a monitoring variable does not guarantee full use of radiation, due to the low efficiency when minimum fluxes are applied, as is the case of 1 m/s at 500 W/m^2 reaching the ideal temperature, but at a minimum efficiency. Therefore, it should be a priority for the research to use the solar radiation present in the area as a reference to establish air flows, seeking to maintain optimal efficiency ranges and adequate temperatures for drying. Maintaining a constant flow of air with temperatures above 40 °C with a collector efficiency greater than 20%, favors drying times, due to the ability to extract steam from the air.

An important factor that must be appreciated by different researchers is the non-uniformity of the paraffin temperature, which follows the same air pattern as observed below.

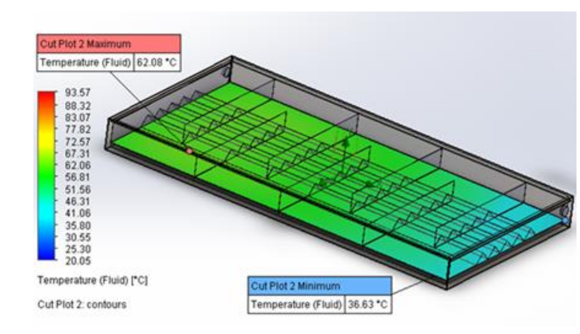


Fig. 7 Paraffin temperature

What the previous image shows is that the material for energy storage does not reach the phase change in its entire volume, so under the different working conditions there would always be a part in solid state and another in liquid state, which implies that it has the capacity to store even more energy. Under these conditions it is possible to apply different types of phase change materials or different types of paraffin, based on their melting point, creating separate storage chambers. This in order to improve the efficiency of energy absorption due to the fact that paraffin has better heat transfer conditions as it is in a liquid state.

IV. Discussion

As part of the initiative for this research, there is an interest in knowing an adequate volume of material for energy storage within the collector, this in order to allow future researchers to decide on the incorporation of these materials within a system of thermal energy, as is a collector. Consequently, this initiative evaluates different points that must be taken into account when defining a volume for energy storage.

- The first and most important is the heat transfer area, because in this case the metal plate, in charge of absorbing solar radiation, transfers the energy both to the air and the paraffin, this must be reasonably distributed throughout the transfer area.
- When applying low volumes of material, it is possible to achieve uniformity in the overall fluid temperature. In contrast, when considerable volumes are applied inside the collector, it is normal to obtain differences in the states, having a liquid and a solid percentage.
- It is not possible to define a volume relation for the solar collector, this because there are different possibilities when it comes to solving problems such as the melting temperature of the material.

It is identified with this behavior that, depending on the specific needs of the drying system, such as an amortization of sudden changes in temperature generated by the sun (changes in irradiation over time), a small volume of paraffin can be used. and of a single type. For those cases in which it is desired to extend the drying times and a large volume of material is required inside the collector, different types of paraffin must be used based on its melting temperature, always looking for the position in which it is located. within it, generate a change in its state from solid to liquid [13], [17], [18].

The constant search to maintain efficiency levels should be a priority when designing and sizing a solar collector. When the investigation begins, it starts with the objective of reaching temperatures close to 60 ° C, but this is not a factor that indicates a correct operation in drying. The main priority is the use of heat, since the increases in temperatures generated in the air contribute to the improvement of its ability to extract the steam inside the products. Therefore, when designing a control system, the measurement of solar irradiation must be taken into account, so that it contributes to the calculation of efficiency [2], [3], [8], [24].

V. Conclusions

With the research carried out, it was possible to have a better understanding of the dimensions required in a flat solar collector for food drying applications such as cocoa and coffee. Due to the energy requirements, it is identified that energy efficiency should be given priority over the temperature range. In the different simulations it was possible to improve the capacity of the air to absorb steam.

Paraffin selection is a critical part of energy storage collector design due to its latent heat storage advantages. A designer may require a different thermal storage material than the one used in this study depending on the energy requirements of the drying system, normal operating temperatures and the storage capacity of the structure. The priority when selecting this material is the melting temperature, because if this limit is not exceeded, the material does not fulfill its function efficiently.

Air flow control and monitoring of solar irradiation become an essential part for the construction of a drying system with the solar collector, due to the importance of making efficient use of the heat generated.

It is recommended for future research work to carry out a complete design, integrating both the collector and the drying chamber, due to the required understanding of the air flow within the dryer. It is important to take into account that there are different drying stages and they depend to a great extent on the type of the product, therefore it is recommended to analyze in more detail the specific needs of the drying of cocoa or other products, to define in which stages a accelerated flow to remove moisture and in which an increase in temperature is required to generate evaporation of the water contained in the center of the product.

The development of an advanced control system, whose monitoring variables are air flow, temperature, solar radiation, among other factors that affect the efficiency of the collector. It becomes a major challenge for the advancement of this type of initiative, due to the complexity represented by the drying of food (product quality) and the transfer of heat and mass. For them, it is advisable to have an interdisciplinary team that contributes to achieving the standards of efficiency and quality of the process.

Regarding the improvement of heat transfer, the incorporation of conductive metallic structures is openly recommended, which improve thermal efficiency when storing heat in the phase change material such as paraffin. There are different studies that also propose the incorporation of metallic nano-particles that mix with the fluid, to contribute to the conductivity.

Nomenclature

C Specific heat $\left({J}/{Kg * K}\right)$

Q Heat (W)

$\dot{m}$ mass flow $\left({Kg}/{s}\right)$

T Temperature (°C)

Greek letters

η efficiency (%)

Subscripts

a absorbed

p constant pressure

T Total

VI. ACKNOWLEDGMENT

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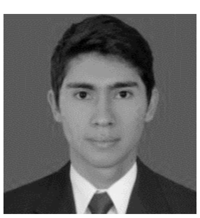

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