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DESIGN OF A SUSTAINABLE THERMOFORMING FOR BIODEGRADABLE SHEETS

DISEÑO DE UNA TERMOFORMADORA SOSTENIBLE PARA LÁMINAS BIODEGRADABLES

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Abstract: Contributing to sustainability is a strategy that has allowed organizations to develop new trends in production activities and technological innovation, helping to mitigate the impact on the environment that the industry makes in the daily life of its processes and procedures, ranging from the reduction of industrial emissions to energy renewal. That is why, through this research, we want to present an alternative design for an industrial solution, revealing the technical aspects that lead to the development of an eco-sustainable thermoformer, that is, one that works through alternative energies, specifically solar energy, with a view to using cassava starch to assemble biodegradable dishes.

Keywords: Thermoforming machine, sustainability, biodegradable, vacuum pump, energy, plastic

Resumen: Aportar a la sostenibilidad es una estrategia que ha permitido a las organizaciones el desarrollo de nuevas tendencias en actividades de producción e innovación tecnológica, contribuyendo a mitigar el impacto al entorno ambiental que la industria hace en la cotidianidad de sus procesos y procedimientos, que van desde la reducción de emisiones industriales hasta la renovación energética. Es por esto, que a través de la presente investigación se quiere dar a conocer un diseño alternativo para una solución industrial dando a conocer los aspectos técnicos que lleven al desarrollo de una termoformadora ecosostenible, es decir, que trabaje a través de energías alternativas, específicamente energía solar, con miras al aprovechamiento de almidón de yuca para el montaje de platos biodegradables.

Palabras clave: Termoformadora, sostenibilidad, biodegradable, bomba de vacío, energía, plástico.

1. INTRODUCTION

The human being in his continuous search to improve the conditions of the environment in which it operates and that contributes to its quality of life, has led to the development of various strategies that enable this goal, hence the sustainable development goals - SDGs (Subramaniam et al., 2023) as a means of defining the results to be achieved and contributing to the goals set. Hence, one of the means they have proposed has been to reduce the impact of pollution on social environments; considering SDGs 7, 12, 13, affordable and clean energy, responsible production and consumption and climate action respectively.

The pollution generated by industry in the processing of plastic products has resulted in the impact of large environments, especially at sea; to that, it can be added that making continuous use of non-renewable energies has generated a number of impacts towards the environmental environment, industrial and social development that has led to the development of actions that lead to a change of perspective and method for the development of processes.

On the other hand, plastic, a by-product of petroleum, has properties that prevent it from naturally degrading. Instead, over time, it fragments into smaller and smaller pieces until it is completely disintegrated, a process that takes about 150 years. It should be noted that plastic acts as a pollutant that accumulates toxic components present in the air, thus amplifying its potential for environmental damage. This demystifies the belief that recycling can significantly mitigate its environmental impact, considering that of the 5.8 billion tons of plastic discarded since 1950, only 9% has been recycled (Buteler et al., 2019).

Hence, plastic pollution has a considerable impact on climate change, as evidenced by the estimated emission of 1.7 gigatons (Gt) of CO2 in 2015, which is projected to reach 6.5 Gt by 2050; moreover, represents 85% of the waste found in the oceans (Rukikaire, 2021)

That is why today we are looking for new materials that represent a lower environmental impact on production processes and their useful life. One of the materials analyzed and that presents a low environmental impact is cassava starch; for (Alexander et al., 2017) the production of cassava in cultivation does not require a soil with high content of nutrients and in the transformation to starch does not require large amounts of water cataloging it as an eco-efficient crop by nature. In addition, the Department of Meta registers about 4% of the total cultivation of Yuca in the national territory, standing out for a sustained increase in the cultivated area (10,714 hectares) (Ministerio de agricultura, 2019) (Aristizábal et al., 2007).

To do this, it is necessary to adapt the different machines and technological tools that are involved in the transformation processes of these new materials and thus achieve incorporate them into everyday life in an optimal and industrialized way facilitating the development and having a positive impact based on responsible production and consumption.

This paper proposes the design of a thermoforming plant for cassava starch that contributes to the mitigation of environmental impacts using photovoltaic solar panels. To contribute with the processes of technological development thanks to the production of biodegradable dishes, which take as main raw material the cassava starch.

2. BACKGROUND

The use of various natural materials for the development of biodegradable fibers has brought with it various studies that are an opportunity in research, such as new businesses and products. This is how the use of cassava fiber to be thermoformed and produce biodegradable dishes, is one of these opportunities presented. This, because Atmaja & Zulnazri (2021) carried out a study using the fruit of the oil palm, which, converted into bagasse, was mixed for the development of a plastic compound, to which various physical-mechanical tests were applied to check the quality and use of this.

Another example, in which plant production is used for its transformation into new materials, are Diaz, Cabrera, Diaz-Idrogo, Chumacero & Gamboa (2023) who made use of potato starch and asparagus to form biodegradable trays through a thermoforming process.

As well as, the fruit of palm oil and potato, banana and cassava are two additional products that led to the design of a biofilm from research Zapata, Ludeña, Pinday, & Barrios (2023), which evidenced an efficient biodegradation process which when compared with conventional plastics showed a much shorter degradation time to the research base mixture.

On the other hand, evidencing the use of cassava starch as a biodegradable material, for its sustainable properties and of renewable origin, added to various studies that attest to the thermal and mechanical properties, this was the conclusion reached López, Mejía, Zavala & Flores (2023).

In activities related to material development, the exposed biomaterials have each been worked through thermoforming; given that it sought to improve properties and contribute to sustainability through the degradation of the products that are developed.

3. METODOLOGY

The research was developed through a descriptive approach where criteria of a quantitative nature were considered associated with the development of calculations for the components that integrate the assembly of the simulated design of the thermoformer, these are: vacuum pump, heating system, solar panel system and costs, among others; the descriptive approach is related to the identification of the background associated with the use of cassava starch in processes of transformation and industrial exploitation. This section shows all the calculations corresponding to each of the components of the raised thermoforming system (vacuum pump, number of solar panels, battery capacity, controller, current inverter).

3.1 Calculation of vacuum pump capacity.

To determine the energy consumption of the thermoforming machine, the pumping capacity equation SP is used

$$Sp = \frac{Vtotal}{t} Ln\left(\frac{P1}{P2}\right) \qquad (1)$$

Where:

S_p, is the pumping capacity
V_{total}, is the total volume of air to be moved
t, is the estimated time of vacuum application
P1, is the atmospheric pressure
P2, is the absolute vacuum pressure required in the Thermoforming process

3.2 3.2 Energy required (E_{req})

$$E_{req} = P_{res} * t_u * F_{ppanel} \qquad (2)$$

Where:

P_{res}, es la potencia de la resistencia
t_u, es el tiempo de uso de la termoformadora
F_p, es el factor de pérdidas en conexiones.

3.3 Cálculo de paneles solares requeridos (N_p)

El número de paneles solares requeridos dependerá de la estimación de la carga:

$$N_p = \frac{E_{req}}{n_{h\,sol}} * F_{ppanel} \qquad (3)$$

Donde:

E_{req}, is the energy required by resistance
$n_{h,sol}$ is the number of hours of sunshine in Villavicencio
F_{ppanel} is the loss factor of the panel

3.4 Estimation of battery capacity (C_b)

In this case it will work with 12 V batteries and it will be assumed that the entire system must have a day of autonomy.

$$C_b = \frac{E_{req}}{V_b} * F_{pb} * D_{aut} \qquad (4)$$

Where:

E_{req}, is the energy required by resistance
V_b, is the voltage of the batteries
F_{pb}, is the loss factor of batteries
D_{aut}, are the days of system autonomy

3.5 Estimation of current regulator capacity (C_{reg})

Its main function is to manage the flow of electricity from solar panels to batteries, protecting the latter from overloads or excessive discharges. The regulator keeps the battery in optimal condition, prolonging its life and ensuring the efficiency of the solar energy system. In addition, it helps to convert the voltage generated by solar panels to the appropriate level for proper storage in batteries.

$$C_{reg} = I_{max} * N_{p\,paralelo} * F_{sr} \qquad (5)$$

Where:

I_{max}, is the maximum current of the solar panel
$N_{p\ paralelo}$, is the number of panels in parallel
F_{sr}, is the safety factor of the regulator

3.6 Estimated current inverter capacity (C_{inv})

$$C_{inv} = P_{res} * F_{si} \quad (6)$$

Where:

P_{res}, is the power of electrical resistance
$N_{p\ paralelo}$, is the number of panels in parallel
F_{si}, is the investor's safety factor

3.7 Estimated CO2 emissions saved

The equation is used to calculate emission savings:

$$EM = w_{req} * EF \quad (7)$$

Where:

W_{req}, is the total power required.
EF, is the emission factor of the national electricity system.

4. RESULTS

This section includes the development of calculations related to the design of components that are part of the thermoforming system.

4.1 Calculation of vacuum pump capacity

In this case, it considered the atmospheric pressure of Villavicencio (28.30 inHg), a vacuum pressure of 5.7 inHg and a suction time of 10 seconds.

$$t = 10\, seg \rightarrow 0{,}17\, min$$
$$Vtotal = 0{,}72ft \times 0{,}72ft \times 0{,}14\, ft$$
$$Vtotal = 0{,}089ft^3$$
$$P1 = 28{,}30\, inHg;\ Atmospheric\ pressure$$
$$P2 = 22{,}6\, inHg;\ Vacuum\ pressure\ for\ thermoforming$$

$$Sp = \frac{Vtotal}{t} Ln\left(\frac{P1}{P2}\right) \quad (8)$$

$$Sp = \frac{0{,}089ft^3}{0{,}14\, min} Ln\left(\frac{28{,}30\, inHg}{22{,}6\, inHg}\right)$$
$$Sp = 0{,}12\, CFM = 0{,}18\, HP = 135W$$

It can be evidenced that the power capacity of the pump is 135w without taking into account the percentage analysis of efficiency of the vacuum pump.

The efficiency percentage of the piston vacuum pump ranges from 60% to 80%. For the case, an efficiency value of 70% was used.

Where:
$$\eta = Pump\ efficiency$$

$$Sp = \frac{135W}{\eta}$$

$$Sp = \frac{135W}{70\%} = 192{,}85W = 200W$$

It is evident that a vacuum pump with a power of 200 W is required.

4.2 Electrical resistance load estimation

Determining the electrical load required by the thermoforming machine involves calculating the energy consumption, considering the electrical resistance of the machine and added to the vacuum pump. In the Table 1 the electrical equipment to be used in the thermoforming, the consumption in watts, the electrical power, the time of use are shown. For this he estimated an 8-hour shift. However, 4 hours were taken into account for the calculation of consumption because the remaining 4 hours were considered to be for the process tooling process. A 10% connection loss factor was considered and a total consumption of 5200 Wh was finally achieved.

Table 1 : Electrical resistance load estimation

Equipment	quantity	Consumption in watts	hours of use per day	Energy consumption (Wh)
Electrical resistance	1	1.000	4	4.000
Vacuum pump	1	200	4	800
Connection loss factor 10%				5.200

4.3 Estimation of solar panels capacity.

In the Table 2 the calculation of the capacity of solar panels necessary to supply the electrical requirement associated with the thermal resistance and the vacuum pump is shown (5200 Wh).

However, the installation and commissioning for the proposed design has been considered in the city of Villavicencio. 6.58 hours of optimal solar radiation were considered Fig. 1. (Ideam, 2023). (as a result, 4 200-watt solar panels will power the electrical system for the thermoforming machine.

Table 2: Estimated capacity of panels

Region location	Corrected load consumption (Wh)	Hours of sunshine (map)	Capacity panels	Number of panels (200 W)
Villavicencio	5200	6,58	790,6	3,95

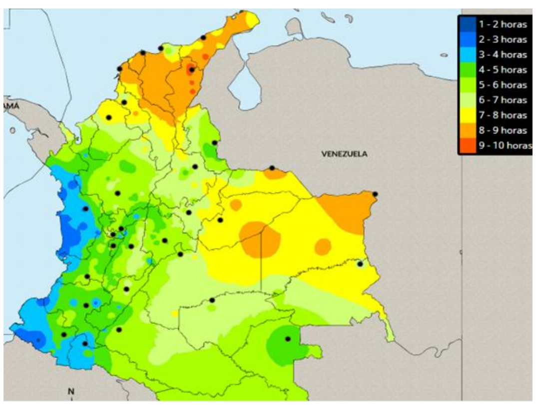

Fig. 1. Solar radiation map (Ideam, 2023)

4.4 Battery charge estimation

Table 3: Battery charge estimation

Corrected load consumption (Wh)	Voltage batteries	Temperature loss factor 30%	Hours of autonomy	Battery capacity (Ah)
5.200	12	1,3	24	23,5

Since photovoltaic systems work from solar radiation, for low intensity moments it is necessary to have elements that contribute to the efficient operation of the machine. Therefore, as a backup system of photovoltaic solar panels, it is necessary to have a battery system with a capacity of 23.5 Ah to ensure that the thermoforming machine will have 24 hours of autonomy Table 3.

4.5 Current regulator estimation

The current regulator is an essential component in a battery-powered solar panel system, as its main function is to protect both solar panels and batteries from damage caused by excessive currents. It acts as an intermediary between solar panels and batteries, controlling the flow of energy to ensure an efficient and safe charging.

Putting into operation the system of photovoltaic solar panels with the capacity required by the thermoforming machine implies that the maximum current required will be 7.5 amperes, considering a safety factor e 25% Table 4.

Table 4: Current regulator estimation

Maximum solar panel current (Amp)	Security factor	Parallel panels	Corrected current (A)
6	25%	1	7,5

4.6 Current inverter estimation

The electrical system requires a current inverter that facilitates the conversion of current from DC to AC to ensure the operation of the elements. The maximum power that would be the sum of the power of the electrical resistance and the vacuum pump was considered and a safety factor of 25% was implemented. Resulting in required inverter capacity of 1500 W Table 5.

Table 5: Current inverter estimation

Maximum power (W)	Safety factor 25%	Voltage batteries	Capacity of the inverter (W)
1.200	1,25	12	1.500

4.7 Estimation of CO2 savings

For the calculation of CO2 emissions saved, the value of the total energy required by the machine, the emission factor of the Colombian national electricity system was used (kg CO_2eq/kWh) (Bonilla et al., 2017) and considered 26 days of operation. Thus, it was estimated that the use of the solar photovoltaic system stops emitting 17 kg of CO2 per month Table 6.

Table 6: Estimation of CO2 emissions savings

Energy required (kWh)	Days of operation	Emissions factor (kg CO_2eq/kWh)	Saving of CO2 emissions (kg)
5,2	26	0,126	17

4.8 Temperature control circuit

The development of the thermoforming machine involves the development of an electrical system that allows the transformation of electrical energy into heat energy, so that the main function of the machine is performed, perform thermal change processes that facilitate the molding process of the dishes.

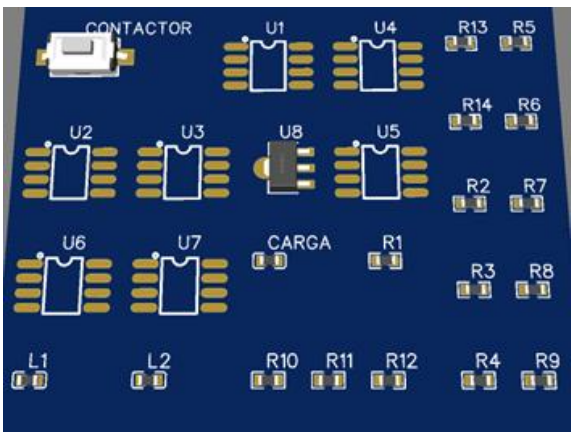

Fig. 2. Model of the thermoforming 3D electrical system.

The construction of the thermoforming machine is supported by an electrical system that has been modeled on the Fig. 2, This system has 14 resistors (R), 8 operational amplifiers of instrumentation (U), 2 signals of inputs L1 and L2 which penetrates the ground system (L) and a charge thermoresistor, as well as the contactor of on and off of the thermoforming.

Each of the components described configure the three base systems for the thermoforming machine to work: The power system, the temperature system and the thermocouple system.

4.9 Power control system

This system allows the transformation of electrical energy to heat energy through an induction process, where the coil generates a magnetic field that produces current by induction. To control the power system, there is a digital controller, which allows setting the regulated temperature.

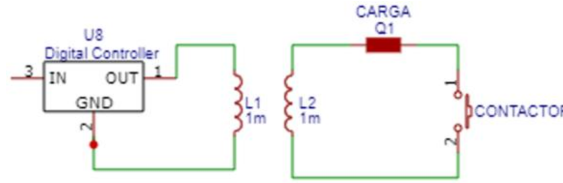

Fig. 3. Power control system of thermoforming machine.

The Fig. 3 represents the distribution of the power system that the thermoforming machine has for the on-off processes. This is distributed in two sections, a first section associated with the contactor; the other section connects the digital controller, in the middle happens the induction process that generates the heat energy and allows the transformation of the material.

4.10 Temperature control system

The temperature control system (T°) is a series-designed circuit composed of three operational amplifiers. This circuit allows that as the current advances the system presents a change of T°, which must increase until reaching the heat energy required to transform the material.

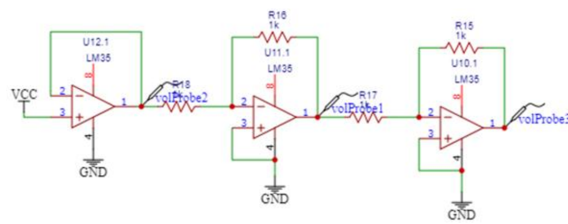

Fig. 4. Thermoforming temperature control system.

The energy input to the system is made through the voltage point - VCC.

4.11 Thermocouple control system

The system for thermal operation of the thermoforming machine is proposed in the Fig. 5, this shows the mode of energy transformation for the machine to perform the process of energy induction and go to heating, achieving a temperature adjustment for the molding of materials and without losing control of these.

A system of thermal change has been arranged starting from an initial temperature which from the progression in the system varies in increase.

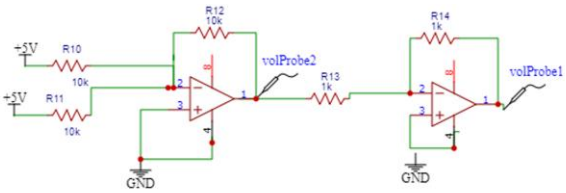

Fig. 5. Thermocouple control system for the thermoforming machine.

The thermocouple system has its input into the model through the +5V points and moves through two operating amplifiers until generating the heat transformation process.

4.12 Imulated design of the thermoforming machine

The design of the thermoforming machine configures elements that make the machine a practical device that allows the adaptation of this to the needs.

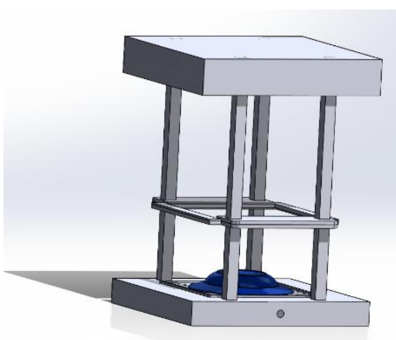

Fig. 6. *Side view of simulated thermoforming design*

The Fig. 6 shows a side view of the thermoforming machine, in the upper part of the figure is located the heating chamber, is where the temperature change is made to shape the product to be developed, in this case, the biodegradable dish of cassava starch. In the intermediate zone, the laminate support is located is the piece on which the material rests to be molded to obtain the final product. At the bottom, is the vacuum chamber which is responsible for the injection of the treated cassava starch.

In the Fig. 7 you can see a different perspective there is visualized from the front each of the elements described above.

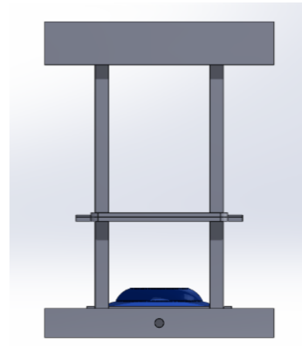

Fig. 7. Front view of simulated thermoforming design

5. CONCLUSIONS

Mathematical calculations are the basis of simulation for the development of any machine, equipment or tool; is for this reason that the design of the thermoforming machine that uses cassava starch for the assembly of biodegradable dishes takes as an incident element the analysis of quantitative information that focus on the energy use and the positive impact on the environment ambiance.

The obtained data lead to determine the energy needs required by the elements that make up the thermoforming machine. Starting from the consumption of 200W that the vacuum pump requires and the average energy consumption that must satisfy the solar panel system which reaches 5,200 kWh for which it is necessary to establish a network of 4 batteries that support the operation of the machine.

The use of solar energy leads to a reduction in CO2 emissions of 17 kilos per month of machine use; likewise, a positive impact can be asserted by reducing the consumption of plastic in thermoforming process, when making use of biomaterials such as cassava starch.

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