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Design and construction of low shear laminar transport system for the production of nixtamal corn dough

Diseño y construcción de un sistema de transporte laminar de bajo cizallamiento para la producción de masa de maíz nixtamalizada

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Abstract

The tortilla is obtained by the traditional process of nixtamalization. This process has two disadvantages: production of liquid waste and it is in batches. Extrusion has resolved the problem of liquid waste, however, extrusion as of yet, has not been able to replace the traditional process of nixtamalization. This is because corn dough is a pseudoplastic fluid, which changes its viscosity in the presence of high shear velocities that occur inside the extruder. With this in mind, the following investigation proposes the mechanical design and construction of a low shear laminar transport system (LSLTS) for the production of corn dough for tortillas. This system consists of two thermally isolated stages: transport and cooking stages. The results showed that the prototype obtained meets the characteristics of homogenous cooking, low shear, absence of liquid waste and the product meets the specifications for nixtamal dough.

Keywords: Mechanical design, nixtamal, low shear, tortilla.

Resumen

La tortilla se obtiene por medio del proceso tradicional de Nixtamalización. Este proceso tiene dos inconvenientes: producción de efluentes contaminantes y ser discontinuo. La extrusión, ha resuelto la problemática de la generación de efluentes contaminantes, sin embargo, no ha podido sustituir al proceso tradicional de nixtamalización. Esto se debe a que la masa de maíz es un fluido pseudoplástico, el cual cambia su viscosidad en la presencia de velocidades de cizalla que ocurren dentro del extrusor. Con base a lo anterior, el presente trabajo propone el diseño y construcción de un Sistema de Transporte Laminar de Bajo Cizallamiento (STLBC) para la producción de masa para tortilla. Este sistema consiste de dos etapas aisladas térmicamente: Etapa de transporte y de cocimiento. Los resultados mostraron que el prototipo obtenido cumple con las características de cocimiento homogéneo, bajo cizallamiento, no produce efluentes contaminantes, y la masa obtenida, cumple con especificaciones de masa nixtamalizada.

Palabras clave: Diseño mecánico, nixtamal, bajo cizallamiento, tortilla.

1. Introduction

In Mexico, the tortilla is the most consumed corn product (made in mills and with instant flours), however, in the United States the principal use of corn is the elaboration of snacks. Nixtamalization is the process used to produce the dough necessary for making tortillas. This traditional process is an environmental problem because it generates great quantities of liquid waste due to the fact that the contaminated water, product of the process, is channeled into the cities' sewage system, thus becoming a serious ecological problem [1-3].

Different investigators have developed alternative methods in an effort to solve the problem of liquid waste; for example, Sánchez Sinencio and González Hernández [4] have reported processes and equipment in order to obtain nixtamal corn-dough based on extrusion and infrared cooking, Figueroa [5-7] has developed ecological processes to obtain nixtamal corn-dough, Martínez [8] built a corn flour plant using a method based on vapor reactors and another method of cooking using radio frequencies (RF), Vaqueiro M. C. [9] patented a process of nixtamalization based on the separation of the corn parts.

One of the most viable alternatives to solve the problems of the traditional process is the use of extrusion. The investigators that have applied this method for the elaboration of tortillas are Duran de Bazúa [10], Martínez Flores [11-12], Gómez Aldapa [13], San Martín Martínez [14], Reyes Moreno [15], Milán-carrillo [16] and Gutiérrez Dorado [17] who developed an extrusion method for the production of corn-dough.

One disadvantage of the process of extrusion is the shear velocities that are generated inside the extruder, which results in a change of viscosity in the material. These changes make the corn-dough obtained difficult to process in the tortilla machines. For this reason, extrusion has not been able to substitute the traditional process in the production of nixtamal corn-dough. However, the extrusion method has many great advantages: it is ecological because it only uses the necessary amount of water for the process, also it is energy efficient compared to gas and it significantly reduces the process time.

For practical purposes, we have decided to use the name raw material to refer to the material produced by the combination of corn flour, water and calcium hydroxide. This raw material shows physicochemical changes when it cooks and reaches gelatinization becoming a Non-Newtonian fluid. This type of fluid changes its viscosity in the presence of shear stresses [18]. For this reason the extrusion has not been able to substitute the traditional method in its entirety because in the traditional method the material is at rest and there is no shear. The change of viscosity is reflected in the quality of the final product [19] such as tortillas and snacks.

In this context, this investigation proposes the development of a Low Shear Laminar Transport System (LSLTS) for the elaboration of instant corn flour for tortillas and/or corn-dough for snacks. The term low shear refers to the fact that the cooked corn dough does not undergo mechanical stress [18].

The basic proposal is to diminish the shear by separating the cooking stage from the transport stage where shear velocities are generated due to the rotative elements of the pump. In order to diminish the shear it is also necessary that the corn dough flows in a laminar manner, in order to obtain low shear the geometry of the cooker is determinate.

2. Methodology and Design

2.1. Methodology

The methodology employed in the design can be observed in Fig. 1, which begins with a series of process specifications in order to carry out the conceptual design of the laminar cooker and transporter. Once the geometry is found that meets the initial specifications, a detailed drawing for fabrication proceeds. Finally, the simulated, conceptual and real data is validated.

The specifications of the LSLTS for the elaboration of nixtamal corn flours or corn dough must have the following characteristics:

1. Transport and cooking stages must be separate to avoid cooking the material at the same time that it's being transported and thus avoiding the presence of shear when the material is undergoing physicochemical changes.
2. The transport and cooking stages must be thermally isolated so that the cooking zone is confined to the cooker.
3. The design of the cooker must be optimum in length and cooking time.
4. The design of the fluid laminar transport system must diminish shear velocities.

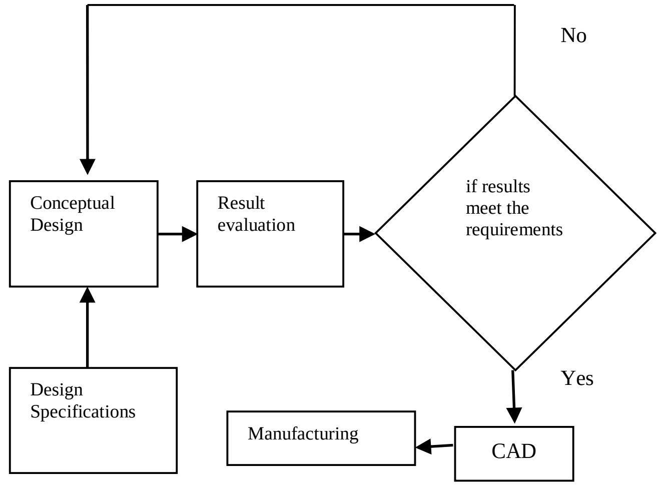

Figure 1. Design Methodology.

2.2. Design

2.2.1. Cooker design

In order to carry out the modeling of the design it is necessary to determine the specification of the machine. Also, it is important to validate the design and cook the material that will be processed in order to determine the mode and ranges of operation. Table 1 shows the rheological characteristics of the material to be processed [20] (Corn flour) and Table 2 shows the gelatinization temperatures of the corn flour [18]. The heat transference in the cooker is regulated by the thermodynamic constants of the material listed in Table 3.

Table 1.
Rheological constants of food for the model of the law of power.

Material	Moisture (%)	Temp. (^0C)	k (Pa*s)	n
Corn grains	13	177	$2.8x10^4$	0.45-0.55
	13	193	$1.7x10^4$	0.45-0.55
	13	207	$0.76x10^4$	0.45-0.55

Source: Adapted from [20]

Table 2.
Ranges of gelatinization.

Sample	Temp. of gelatinization (^{0}C)	Enthalpy of gelatinization (J/g)
Corn dough	70.7 ± 0.7 to 78.1 ± 0.7	14.7 ± 1.0

Source: Adapted from [18]

Table 3.
Thermodynamic constants of corn flour.

Product	k $exp.$ $(\frac{W}{m\,^0C})$	Cp $(\frac{W}{m\,^0C})$	α $\frac{(m^2)}{s}$	k $calc$.$(\frac{W}{m\,^0C})$
Corn dough	0.40	2.64	1.4 x10^{-1}	0.42

Source: Adapted from [21]

According to the previous information it can be concluded that the temperature of the material while exiting the cooker should be within a range of 70.7^{0}C to 78.1^{0}C. Furthermore, the temperature of the walls of the cooker should not go beyond 100^{0}C because the water content of the material can evaporate and form vapor bubbles inside the cooker.

The proposed yield for the cooker design is 1.5 Kg/h as demonstrated in Table 4.

Table 4.
Parameters of the cooker design.

Parameter	Value
Mass Flow	1.5 Kg/h
Internal surface temperature of the cooker	79 ^0C
Material temperature exiting the cooker	76.5 ^0C
Material temperature entering the cooker	30 ^0C

The geometry used for the cooker is rectangular as demonstrated in Fig. 2. This configuration is ideal for the process due to the fact that the entrance and exit are identical and there are no changes in pressure or velocity internally. Another benefit of this configuration is that the material is obtained in laminar form, which reduces shear.

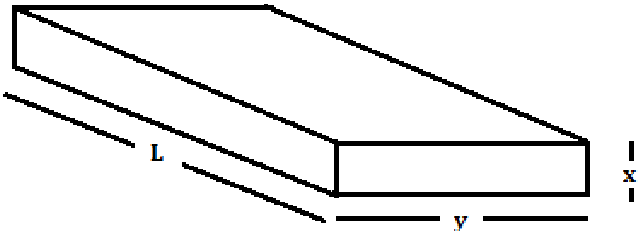

Figure 2. Dimensions of the rectangular cooker.

In order to determine the dimensions, it is necessary to characterize the cooker using thermodynamic equations for the transference of heat with a forced internal flow as shown in Fig. 3.

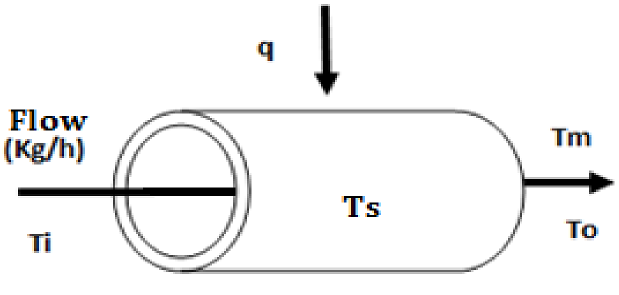

Figure 3. Transference of heat by convection.

The eq. (1) describes the transference of heat by convection in a fluid through a duct $(\frac{\Delta T_o}{\Delta T_i})$with a certain mass flow (m) [22]. Due to the fact that the constant of convection h varies according to the geometry of the cooker, it is necessary to use a correlation with a Nusselt number (N_{uD}). Because the nixtamal corn flour is a pseudoplastic fluid, Nusselt is proposed for non-Newtonian fluids with variable viscosity as demonstrated in eq. (2) [22]:

$$\frac{\Delta T_o}{\Delta T_i} = \frac{Ts - T_{m,o}}{Ts - T_{m,i}} = exp(-\frac{\mathrm{P}}{\mathrm{m}\,Cp}h') \tag{1}$$

$$N_{uD} = \frac{h\,D}{k} = 1.86\left(\frac{N_{Rey}\,N_{Pra}}{L/D}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{1/4} \tag{2}$$

Where P is the duct perimeter, Cp is the specific head, D is the duct diameter, L is the duct length, k is the thermal conductivity coefficient, μ is the viscosity, N_{Rey} is the Reynols number and N_{Pra} is the Prandtl number.

Isolating the constant of convention h in eq. (1) and eq. (2). The following equations are obtained respectively:

$$h = \frac{Ln\left(\frac{\Delta T_o}{\Delta T_i}\right)m\,Cp}{P\,L} \tag{3}$$

$$h = \frac{k}{D}1.86\left(\frac{N_{Rey}\,N_{Pra}}{L/D}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{1/4} \tag{4}$$

Combining eq. (3) and eq. (4), the length of the cooker is obtained:

$$L = \left(\frac{Ln\left(\frac{\Delta \mathrm{T_o}}{\Delta \mathrm{T_i}}\right)m\,Cp\,D^{2/3}}{1.86\,k\,P\,(N_{Rey}\,N_{Pra})^{1/3}\left(\frac{\mu}{\mu_S}\right)^{1/4}}\right)^{3/2} \tag{5}$$

The eq. (5) is for cylindrical ducts. In order to obtain the equivalent in rectangular the diameter D is substituted for the hydraulic diameter in a rectangular duct:

$$D_h = \frac{2\,(xy)}{x+y} \tag{6}$$

Substituting eq. (6) in eq. (5), the result is:

$$L = \left(\frac{Ln\left(\frac{\Delta \mathrm{T_o}}{\Delta \mathrm{T_i}}\right)m\,Cp\left(\frac{2\,(xy)}{x+y}\right)^{2/3}}{1.86\,k\,2y\,(N_{Rey}\,N_{Pra})^{1/3}\left(\frac{\mu}{\mu_S}\right)^{1/4}}\right)^{3/2} \tag{7}$$

The dimension $x = 0.01\,m$ is therefore proposed and the dimension y and the length are estimated with the eq. (5).

$x = 0.01\,m.$
$y = 0.1\,m.$
$L = 0.2\,m.$

2.2.2. Assisted Computer Design for the Cooker

The mechanical design assisted by computer or CAD

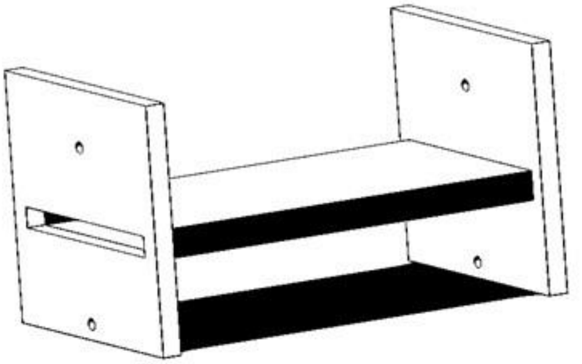

Figure 4. Isometric View of the cooker

(computer-aided design) was developed in SolidWorks 2009 with the following dimensions:

$x = 0.01$ m.
$y = 0.1$ m.
$L = 0.2$ m.

Fig. 4 shows the isometric view of the cooker.

2.2.3. Laminar Transport Design

The design is based initially on the vane pumps with modifications according to the requirements of the cooker. This design proposed that the transporter has a mass flow of 1.5 Kg/h and an exit with the same geometry as the cooker so that there are no changes in pressure or alterations in the flow lines.

The first step is to determine the caudal necessary to pump 1.5 Kg/h. The mass flow and the density in the eq. (8) are substituted and the result is:

$$Caudal(\frac{m^3}{min}) = \frac{m(\frac{Kg}{\min})}{\rho(\frac{Kg}{m^3})} \qquad (8)$$

Where the m is the mass flow and ρ is the density.

$$Caudal = \frac{\left(1.5\,\frac{Kg}{h}\right)*(1\frac{h}{60}min)}{(\frac{1204\,Kg}{m^3})}$$

$$\underline{Caudal = 2.07x10^{-5}m^3/min}$$

Once the necessary caudal is obtained, an estimate is made as to how many revolutions the mixture must make. In this case it is proposed that the caudal make 1.5 Kg/h in 15 rev/min *(n)* in order to determine the capacity in cubic meters necessary for the material contained in the transporter in one revolution. This capacity is the displacement in the eq. (9). When the values are substituted, the result is:

$$Displacement = \frac{Caudal}{n(\frac{rev}{\min})} \qquad (9)$$

$$Displacement = \frac{2.07x10^{-5}m^3/min}{15\;rev/min}$$

$$\underline{Displacement = 1.38x10^{-6}m^3/rev}$$

The use of a stainless steel tube of 47mm in diameter is proposed to design the transporter. According to the stator and the displacement, the dimensions of the vanes and rotor are determined.

2.2.4. Assisted Computer Design for the Laminar transporter

According to the estimated dimensions, the dimensions of the laminar transporter can be determined. The first element that must be designed is the vane with holes to contain 6 mm springs as shown in Fig. 5.

The next pieces that must be designed according to the specifications are the stator and the rotor as shown in figure 6 and Fig. 7 respectively. In Fig. 8 the assembly of the stator, rotor and the vanes is shown. Finally, Fig. 9 shows the complete assembly of the laminar transporter.

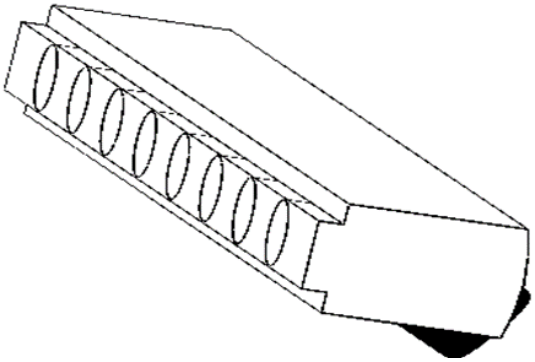

Figure 5. Vane Design of the laminar transporter.

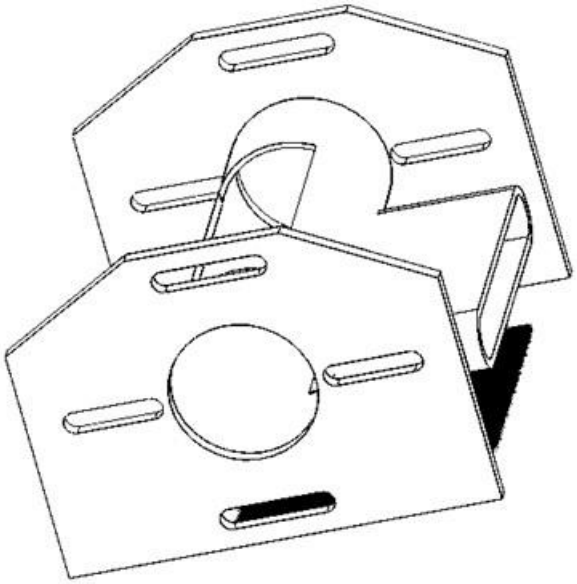

Figure 6. Stator for the laminar transporter.

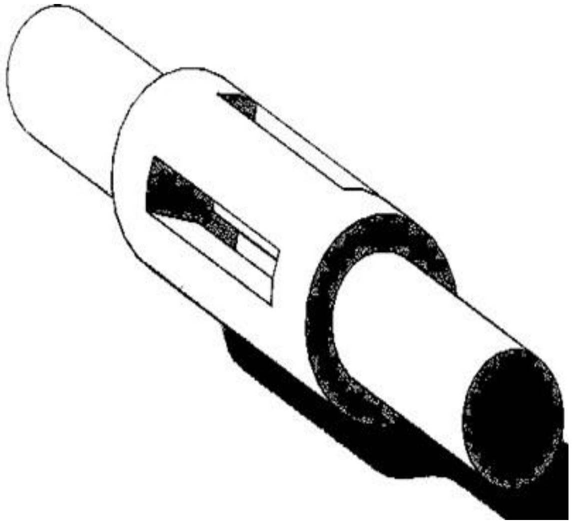

Figure 7. Rotor for the laminar transporter.

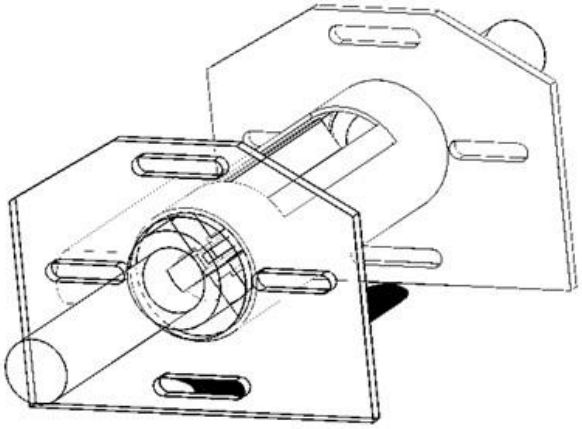

Figure 8. Assembly of rotor, vanes and stator

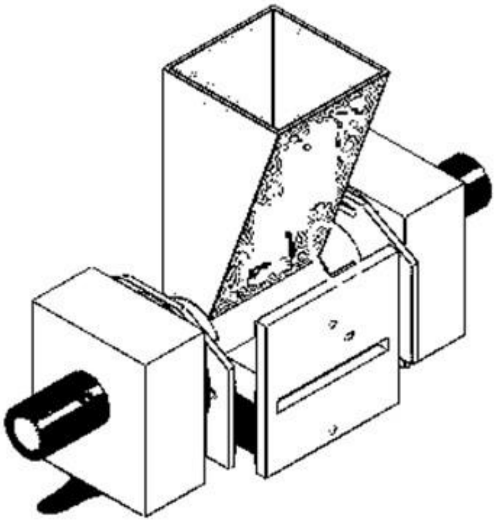

Figure 9. Laminar Transporter.

2.3. *Manufacture of the LSLTS*

The material that was selected for the thermal isolator was Bakelite due to its thermal isolating capacities with a very low coefficient of conduction of 0.233 (see Table 5). Stainless steel was selected for the cooker due to its capacity to conduct heat and its food grade characteristics. As a result of the selection of materials, the isolator was manufactured as shown in Fig. 10.

Table 5.

Max. ρ $\left(\frac{Kg}{m^3}\right)$	$CP\ \left(\frac{W}{m\,^oC}\right)$	$k\left(\frac{W}{m\,^oC}\right)$	α $\left(\frac{m^2}{s}\right)$	*Temp.* (°*C*)
1270	900	0.233	0.201	140

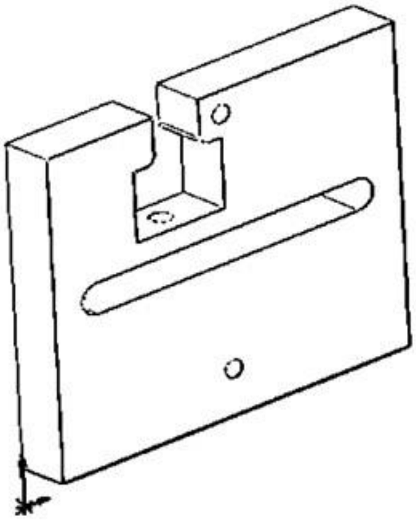

Figure 10. Manufacturing of the isolator.

Fig. 11 shows a representation of the CAD assembly and the mechanical manufacturing of the LSLTS. In Fig. 12 the isometric view of the construction of the LSLTS can be observed.

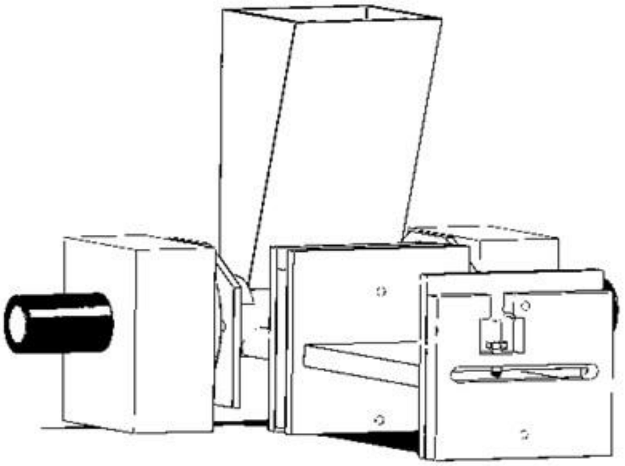

Figure 11. Assembly of CAD and LSLTS.

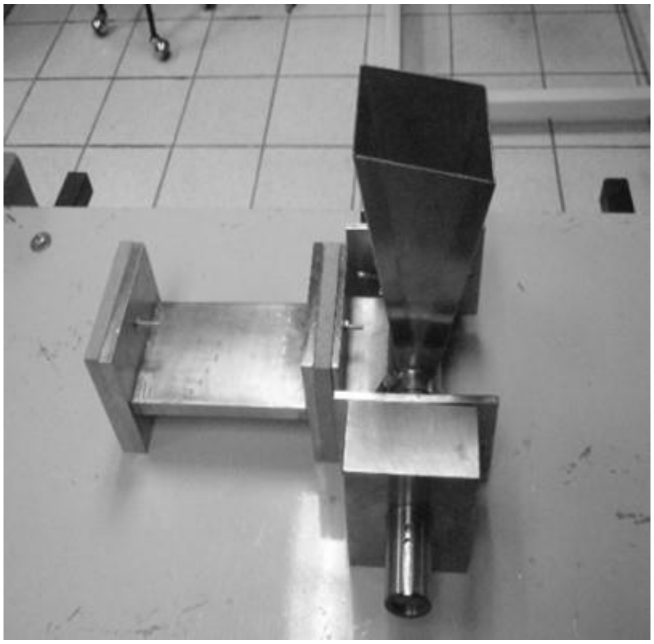

Figure 12. Isometric view of the LSLTS.

3. Tests and Results

Tests were run at the CICATA campus Querétaro with a temperature of 79 centigrade in the cooker, as proposed, and corn flour with a humidity of 55% and a granulometry of 1.3. Four things were tested: flow, temperature, viscosity, and water absorption index.

3.1. Flow test

In order to affirm that the implementation of the transporter meets the requirements of the design, tests were done with corn flour at 55% humidity and the range was varied between 10 and 20 rev/min. The results are shown in Table 6.

Table 6.
Results of the yield of the laminar transporter.

Velocity (rev/min)	Time (*h*)	Weight (*Kg*)	*Kg/hr*
20	0.1	0.2815	2.815
20	0.1	0.291	2.91
20	0.1	0.295	2.95
15	0.1	0.18	1.8
15	0.1	0.17	1.7
15	0.1	0.166	1.66
10	0.1	0.1605	1.605
10	0.1	0.1496	1.496
10	0.1	0.1523	1.523

In the table above it can been observed that the transporter pumps approximately 1.5 Kg/h at 10 rev/min.

3.2. Temperature Test

The objective of this test is to determine if the material reaches the desired temperature when exiting the cooker. In this test it is assumed that the dimensions of the cooker estimated by the theoretical method and the simulation are ideal and will concur with the results of the experiment.

During this test a range of yields of 3 to 1.5 *kg/h* were tried using the velocity control on the motor connected to the extruder. The results can be observed in Table 7.

Table 7.
Temperature Results.

Performance (kg/h)	In Temp. (°C)	Out Temp. (°C)
2.95	33.4	73
2.91	33.8	73
2.81	31.5	72.3
1.8	33.7	77.2
1.7	33.5	76.9
1.66	33.7	77.8
1.60	32.9	77.8
1.52	32.1	77.1

Finally, a comparison was made between the experimental results, theoretical results, and those obtained in the simulation as shown in Table 8. In this comparison a yield of 1.52 *kg/h* was selected due to the fact that it is the value that most closely adheres to those proposed by the theoretical method and the simulation (1.5 *kg/h*). Because the entrance temperature varied according to climate temperature, the error was estimated by taking into account the increase in temperature of the material as it passed through the cooker.

Table 8.
Comparison of results.

Parameter	Theoretical Results	Experimental Results
Performance	1.5	1.52
In Temperature	30	32.1
Out Temperature	76.5	77.1
Delta Temperature	46.5	45
% Error	0	-3.2258

3.3. Viscosity Test

As mentioned above, the viscosity plays an important role in the material obtained. If the viscosity is different, the material is difficult to process in tortilla machines and this changes the physical characteristics of the final product, the tortilla itself. In this test the raw material had a humidity of 55%, 0.35% lime and a velocity of 6 rpm. The test temperature was 79 °C ± 1°C in the cooker The variation in temperature is due to the compensation by the controller. This compensation produces slight changes in viscosity as shown in Table 9.

Table 9.
Viscosity Results.

Sample	Moisture (%)	Vel. (rpm)	Lime (%)	Temp. (°C)	Viscosity (cP)
1	55	6	0.35	79	1379
2	55	6	0.35	79	1320
3	55	6	0.35	79	1514
4	55	6	0.35	79	1441
5	55	6	0.35	79	1751
6	55	6	0.35	79	1751

4. Conclusions

A low shear laminar transport system (LSLTS) was built for the elaboration of corn dough used in the making of tortillas. The transportation of the raw material was by means of vane pumps, whose length was modified, and the cooking by means of a laminar cooker. The term low shear refers to the following mechanical characteristics: an open system without a die, vane transport instead of screw which allows for slow revolutionary operation, and a cooker with rectangular geometry that homogenizes the cooking of the raw material and thus avoids over-cooking by reducing the force of friction.

The LSLTS was designed based on thermodynamic equations which yielded the proposal of a rectangular cooker with the dimensions $x = 0.01m$, $y = 0.1m$ and $L = 0.2m$ in which shear velocities of $0.06\ s^{-1}$ with a laminar flow were generated. This shear velocity is below of the value at which nixtamal corn dough begins to show changes in viscosity. Therefore, it can be concluded that this design does not change the rheological properties of the end product.

The viscosity values obtained are within the reported range. Gruntal reported viscosities of 1.983 to 2.202 $P{\cdot}s$ for nixtamal corn flours by varying the soaking time, Gaytán [23] of 1 to 4.5 $P{\cdot}s$ for nixtamal corn flours by ohmic heating, Palacios [24] of 1.5 to 2.5 $P{\cdot}s$ for commercial nixtamal corn flours and the values obtained in this investigation oscillate between 1.32 and 1.75 $P{\cdot}s$. Therefore, it can be concluded that the LSLTS is low shear and does not have any significant affects on the viscosity.

As a result the system was patented in Mexico MX/a/2012/003687.

5. Acknowledgements

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