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Use of the rolling mill in the extraction of maguey's juice

H. M. Duran-Garcia [1*], E. J. Gonzalez-Galvan [1] and Pastor Ortiz Matadamas [2]
[1] School of Engineering, Av. Dr. Manuel Nava 8, Zona Universitaria, Universidad Autónoma de San Luis Potosí, 78290 México.
**e-mail: hduran@uaslp.mx, egonzale@uaslp.mx [2] Ciidir-Oaxaca, México. e-mail: pmata@ipn.mx*

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Abstract

The extraction of maguey's juice is carried out in a mill that consists of a heavy stone-wheel that rotates impelled by a horizontal axis. The motion of the system is generated by a vertical axis in the center of the mill, which is driven by an internal combustion engine, an electric motor and/or work animals. Once extracted from the oven, the heads of maguey are deposited inside of the mill's workspace, where they are cut with an axe in order to facilitate crushing by the stone wheel. The objective of this work consisted of carrying out an analysis of the effect of the rolling element on the efficiency of extraction of the juice by means of the destruction of the maguey pineapples and to determine the best option out of seven analyzed mills. A study of the principle of operation of the system was made with the purpose of improving or optimizing its technical characteristics. It was determined that the rolling wheel uses the combined principles of pressing, rubbing, smashing, crashing and cutting; achieving the objective of breaking, milling, cutting, whetting, sharpening, bending, breaking and crushing the cells of the maguey pineapples. The efficiency in the extraction of juice was increased with a low volume of sludge.

Key words: Maguey mill, size reduction, extraction of juice, pineapples.

Introduction

The mezcal is an alcoholic drink obtained from sugar contained in the mature heads of magueys [1]. However, the use of maguey for both mezcal production and forage source has affected the natural ecosystem due to an excess of exploitation. With the purpose of avoiding this deterioration it is necessary to improve the efficiency in the extraction of juices. With this objective, it is possible to characterize the mill carried out in mezcal-production units in two types: manual mill and mill aided with animals or driven by engines. Manual mill has practically disappeared due to the great physical effort required to perform it; the mill that uses a stone wheel propelled by animals or by an engine is typical in places that in a continuous way produce mezcal, which production is intended for the national and international markets. The stone is coin-shaped and made of quarry or concrete, jagged or flat, with an approximate weight of half ton. It rotates on a stone or concrete floor, formed in such a way that allows the formation of a circle of approximately 4 m in diameter. The axis and wheel are joined by a timber that crosses the wheel trough its center and acts as the horizontal axis used to move the stone (Fig. 1). The pineapples extracted from the oven are deposited in the space that the stone travels and its size is reduced with an axe, facilitating both the rotation of the stone and the crushing of the pineapples. The objective of this work was to analyze the efficiency of extraction of the juice considering the optimal parameters for the destruction of the maguey pineapples, using the rolling wheel. This requires a study of the principle of operation of the mentioned mill, taking into account that milling is a complicated process and depends on different characteristics, for example, material type, size, forms, hardness, humidity, homogeneity of the material, tool type, resistance to the fracture, resistance to the compression, module of elasticity and technological values of the machine, among others.

Materials and Methods

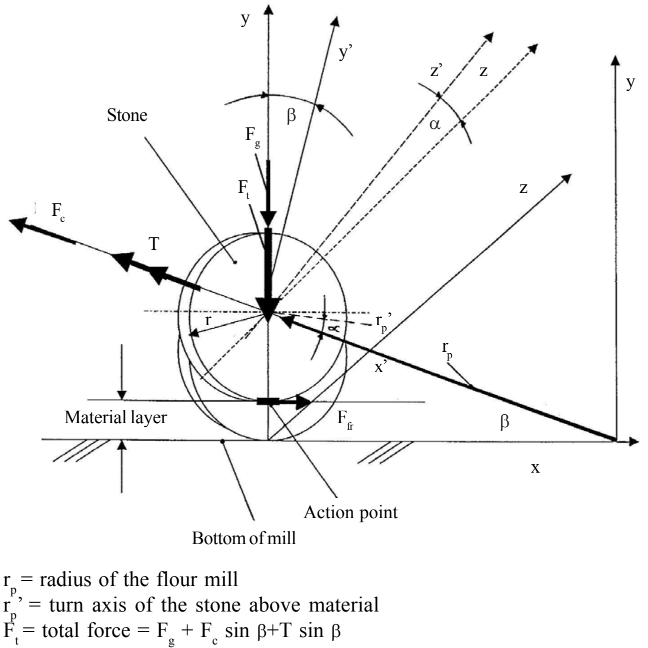
The work was focused on the analysis of the systems of production of seven mezcal-production units and to know the operation elements, as well as means and mill techniques with the purpose of selecting the best parameters for the milling process, through the analysis of the design, the construction materials, the technological parameters and the advantages and inconveniences of the construction.

Results and Discussion

In order to mechanically open the cells of biological materials, the principles of pressure, friction, blow, crash, court, torsion and their combinations are used. When applied, phenomena like breaking, milling, cutting, whetting, sharpening and crushing are present. The selection of the appropriate machines for these processes is limited, due to the characteristics of this material. Important aspects in the milling of this material are the friction and cut resistance of the organic mass of the maguey. Due to the presence of solid and liquid material in the plant, there are three basic elements in the model, namely, viscous, elastic and plastic body. From the energy point of view, the machines that work under the principle of cut through slipping reduce the size of this material more effectively, but the quantity of open cells is smaller compared with other cut principles. Impact and crash is used in machines with hammer-type mills; in these the cells open up more compared with cutting.

Figure 1. Parts of a Chilean or flour mill: 1 Grinding stone; 2 Rod; 3 Joint; 4 Central axis; 5 and 9 Arm; 6 Arm-wheel union; 7 Stone wheel; 8 Profile; 10 Hauling point.

The machines of the type of rolling wheel with central axis (pivot) apply in their operation the combined effects of pressure, friction, blow, crash and cut (see Fig. 2), where the forces $F_{fr}=(F_g+F_t)$ are added, μ= force of friction for radial slipping, $F_t= F_g+\sin\beta(F_c + T)$= vertical force consisting of the centrifugal force plus the force of the polar moment of inertia times angular acceleration, F_g= force due to the weight of the stone; M_T= twisting moment for the horizontal axes (angles α and β). These loads prepare the material appropriately for a simple and complete extraction of juices. The inconvenience present when using the rolling mill is the great space in the construction, the voluminous machine, the supply and the discharge of the material, i.e., the technological integration of the mill is more complicated when compared to the use of a hammer-type mill. The extraction of liquid of the material milled in the hammer-type mill is more efficient regarding the quantity, the cleanliness and the continuity of the process, but with more solid sludge in the juices.



r_p = radius of the flour mill
r_p' = turn axis of the stone above material
F_t = total force = $F_g + F_c \sin\beta + T \sin\beta$
F_g = weight of the stone
F_c = Coriolis' force = $m\, r_p\, w^2$
T= Qf= inert polar moment; f= angular acceleration
F_v= rise of vertical force due to dynamic effects= $F_c \sin\beta + T \sin\beta$
β = rotation of the axis of the stone with respect to a horizontal axis
F_{fr} = skid's friction force

Figure 2. Forces acting during milling process.

Evaluating the efficiency of the energy use in the mill doesn't represent an economic value, because the performance coefficient is very low. Therefore the study of the theory for the reduction of products by means of mechanical tools, with the purpose of maximizing the extraction of juices, is preferred. Two theories exist, that of space (volume) and that of surface [2]. The reduction in size is possible due to the destruction of the molecular adhesion forces.

The theory of space is only applicable for stresses in the elastic range. The reduction in size always requires exceeding the limit of ultimate resistance of the material and its calculation is approximate. On the other hand, the surface theory explains better the mill process of cereals and the theory of space is more useful for explaining the mill process of blowing and pressing big particles (volume); the work required for this purpose is proportional to the surface of the products that will be reduced in size: the larger surface requires more open cells for the extraction of the juice. The reduction of the size of the materials is the division of the material in smaller pieces. In this process the molecular forces of adhesion are broken by the mechanical tools and new surfaces for the particles are generated. The mill process is complex and it is function of such characteristics like material, size, form, hardness, humidity, homogeneity of the material, resistance to the fracture, resistance to the compression, module of elasticity and technological features of the machines. The surface theory starts from the following hypothesis: the work for the reduction of the size is proportional to the new surface of the particles. For example, a cube of 10 mm per side decreases halfway the size by means of a perpendicular cut, using a certain amount of work A. In order to reduce a cube of 10 mm per side in cubes of 5 mm per side, the original cube will have to be cut off by 3 cuts, requiring three times the work A. When three cuts are carried out they produce $2 \times 2 \times 2 = 2^3 = 8$ small cubes. This way when a body (cube) of 10 mm per side is divided in cubes with size 1/n, a total 3(n-1) cuts are required for the partition. Therefore, a work A_n= 3A(n-1) is required; in order to reduce the cube to a size of 1/m per side, a work A_m= 3A(m-1) is needed.

A_n and A_m represent the work necessary for the reduction of a cube by 3(n-1) or 3(m-1) cuts. Letters n and m indicate the steps in the reduction of the material and show how many times the original size is decreased. In this case, the required relative work is determined as: A_n/A_m= 3A(n-1)/3A(m-1)= n-1/m-1; therefore the work required for the reduction of the size of the material is proportional to the corresponding step of reduction. The application of the surface theory specifies that if the size of the cube is not of 10 mm of side, this has the value B. With the steps (m and n) of the size reduction to the values b1 and b2, one has $n = B/b_1$ and $m = B/b_2$ and with these values the work A_n= 3A (B/b_1-1) and A_m= (B/b_2-1) is obtained. The cut area is B^2 and not 10 mm^2. Therefore, the required work can be evaluated with the following relationship, A_1/A_2= $3A(1/b_1-1/B)/ 3A (1/b_2-1/B) = b_2/b_1 x(B-b_1/B-b_2)$.

The above means that more work is needed in the case of finer sizes as compared to big sizes. With these equations, a method for comparing different mills with different design parameters and different materials is available. The theory of space is used to calculate the necessary work for the deformation of the material and, from the theory of the elasticity, it is known that the work for the compression of a material is $A= \sigma^2V/200E$, where σ= compression stress in kp/cm^2; E= module of elasticity (for the organic mass of the maguey pineapple = 1000 - 5000 kp/cm^2 of dry material with 12% of humidity); V= volume of the material reduced in size (cm^3). From the previous equation and with the purpose of comparing the effect of the work we have $A_1/A_2 = V_1/V_2 = a^3_1/a^3_2 = F_1 x\ s_1/F_2 x\ s_2 = F_1 x\ a_1/F_2 x\ a_2 = a^3_1/a^3_2 = F_1/F_2$, where a_1 and a_2 are the sizes of the particles, F_1 and F_2 are the necessary forces for the size reduction: s_1 and s_2 represent the magnitude of the deformation and change from s_1/s_2 to a_1/a_2. Therefore, based on the theory of space, the work required for the reduction in size is proportional to the volume and the force needed for the reduction in size is proportional to the cut area of the materials that will be reduced.

The important parameters in the process of reduction of size are force to cut the material F (kp), stress σ_d (kp/cm^2) and the absolute reduction s (mm), besides the structure of the material and mill type. Generally, the work required for the reduction in sizes consists of three elements: the energy of the surface, the physical work for the reduction of the size and the technical work for the reduction in size. In order to generate a new surface, in the case of the surface energy, energy is needed and this is obtained through the elastic energy and the deformation of the solid material. Real bodies are not homogeneous, they have no order, internal cracks, gaps and different internal materials; these flaws are the cause of fracture. The first fracture begins with the biggest flaw; the density of structural flaws defines the fine size of the mill process and it defines the physical work of the reduction of sizes. The physical work for the reduction of the sizes is a function of several aspects like the structure of the body, size of the material, temperature, load type and time of action of the load. The technical work includes the additional physical and lost work; the superficial energy is similar to 1% of the physical work and the physical work is 10% of the technical work.

Then about 90 to 95% of the work (energy) is lost (work lost). For this reason it is more important to the effectiveness of the extraction for the different effects of milling and compressing. The capacity to mill a solid material is not only a function of the hardness, but also of the thickness of the material. Therefore, the selection of the mill is fundamental for a good preparation of the material, achieving a maximum technological integration in the production process. A cut for slip reduces the force required to mill and if the surface of the chip is very rough, i.e., an extensive surface with great topography, the extraction becomes simple and effective. Besides, due to the plastic deformation of the vegetable material, the force of friction between the cutter and the material is reduced. Therefore, the mills of rolling wheel are excellent for the extraction of juices but with a complicated integration in the process. An important aspect in the mill is the one related to the energy of deformation (U) which is the work performed by the loads:

$$U = W = \int^{\delta} F_1 d\delta_1 \qquad \text{with } \delta = \frac{F^* L}{E^* A} \text{ to obtain}$$

$$U = W = \frac{F^2 {}^* L}{2^* E^* A} = \frac{E^* A^* \delta^2}{2^* L}$$

This means that an increment of the force above the material represents a squared increment in the quantity of necessary energy; the same thing happens with deformation (δ). Therefore a slow process is more efficient energetically; the stone mill (slow pressure) is better than that of hammers (quick cut). The energy of deformation is sometimes defined as internal work in order to distinguish it from the external work W. In general the total deformation can be determined by means of the equation:

$$\delta = \sum_{i=1}^{n} \frac{F_i L_i}{E_i A_i}$$

where F_i= force; L_i= material length (thickness); A_i= area of the material that receives the stress; E_i= module of elasticity (which is a function of liquid mass, solid mass, structure and texture).

$$E = \frac{F_B {}^* L^3}{48^* f^* I}$$

where F_B= bending force above the material; L= longitude of the trunk; f = deformation of the material; I= moment of inertia of the cut area.

As a result, the vertical loads (Fig. 2) like weight and centrifugal force, as well as the horizontal forces, like the cut force, the skidding force due to translational and angular displacement, accumulate to produce a bigger resulting deformation than that of the partial deformations (Fig. 3). The same result is present by the accumulation of the axial and shear stresses. That is the cause of a complete destruction of the organic material that facilitates the extraction of the juice.

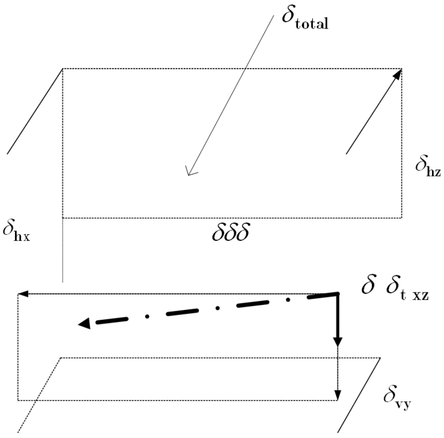


Figure 3. Material deformation as a consequence of the different stresses in maguey.

The objective of the milling process is to increase the force of the mill over the material and to increase the area of the surface of the material. The module of elasticity (E) cannot be changed mechanically, only with thermal, biological and chemical means. Also, it is possible to increase the normal force on the material through the following measures: 1) by increasing the weight of the stone (m* g), 2) by increasing the vertical component of the twisting moment of acceleration (Fig. 2) which means: great radio = great force for $J_p = A^* r^2$ y $\theta = J_p/r$ with exponential effect, 3) by increasing the vertical component of the centrifugal force $F_c = m^* r^* \omega^2$, 4) by introducing a horizontal component of superficial friction of the material of the maguey and the internal force of the mechanical system of the mill: $F_r = F_N {}^* \mu$ as a result of the skidding angle between the axis of the stone and the center of the platform (bottom), together with the rotation of the axis of the stone in two directions (yy =β y zz =α) and the static coefficient of friction of the maguey with 35% of the dry mass, over an iron sheet which varies from 0.61 to 0.69 and the density of mass of the maguey which has a value from 620 to 680 kg/m^3, 5) a Coriolis force exists due to skidding ($F_{co} = 2 * m * v * \omega$) and acts between the stone and the material that moves inside of the revolving system. Such a force acts perpendicularly to the relative motion of the material and 6) increasing the pressure on the material by means of the reduction of the contact area, modifying the profile of the stone.

The total deformation, important for the extraction of the liquid, is the vector sum of deformation in the horizontal and vertical axes and in the twisting or torsion direction:

$$\delta_{total} = \delta_{hx} + \delta_{hz} + \delta_{vy} + \delta_{tzx}$$

The area of action of the pressure produced by the wheel of the mill on the maguey mattress can be considered similar to the structure and density of the floor under the wheel of a vehicle by means of the equation [3]:

$$z = \left[\frac{3w}{(3-n)(k_c + bk_\phi \sqrt{D})} \right]^{\frac{2}{2n+1}}$$

where z = depth of action of the load (pressure) in the material (maguey mattress); w = vertical load; $n = \tan\alpha$ = angle of the slope of stress in the circle of Mohr; k_ϕ= module of elasticity for the compression of the material; k_c= shear module of elasticity of material; D = diameter of the wheel.

With this equation it can be observed that the pressure diminishes as the depth (thickness of the mattress) is increased. The data in Table 1 and Figs 4 and 5 show clearly the previous information, because with a thickness of the mattress of 42 cm and 29 turns (38-40%) the percentage compression is more reduced in comparison with a thickness of the mattress of 25 cm and 10 turns (60-70%). Therefore, the reduction of the thickness of the mattress increases the extraction of juices by means of the action of the pressure, but with a reduction in the time of action of the pressure (10 turns) compared to 29 turns as in the other case. The time of action of the pressure has in this case smaller importance when compared to the magnitude of the pressure (stress) in the maguey mattress.

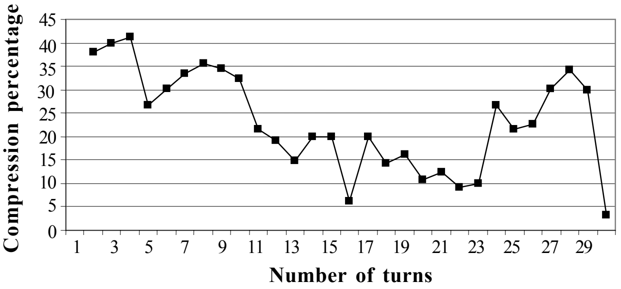


Figure 4. Compression percentage at the Saldaña mezcal factory.

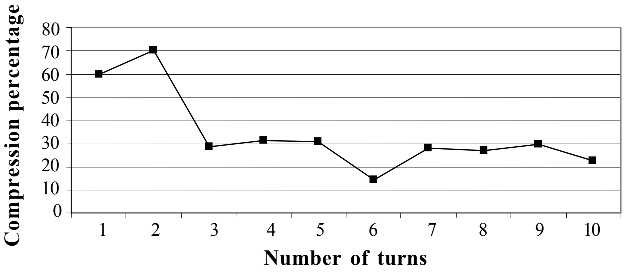


Figure 5. Compression percentage at the Laguna Seca mezcal factory.

Conclusions

The mill that showed better results of the seven cases that were analyzed was the one of Santa Teresa 2 and it was found that: a) the effective pressure is increased with an additional weight, the central radius increases the vertical pressure due to the centrifugal and Coriolis force; b) the angle alpha is important for the increase of the deformation of the material; c) it is useful that the channels on the surface of the stone are directed toward the center of the mill with the objective that the juice comes out in the direction of the forces of the compressed material; d) the angular velocity has little influence on the pressure for the small increment and the reduction of the time of pressure is important for the extraction; e) the acceleration is very small, then it doesn't have significant importance; f) the coefficient of friction is important for a great deformation in the radial direction, for that reason the cavities in the surface of the stone are very useful for increasing of the coefficient of friction; g) the moment of inertia together with the acceleration has little importance; h) the contact area has to be small, in order to increase the pressure; i) the density of the wheel has to be the maximum available.

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Table 1. Characteristics of mills.

Characteristic	Laguna Seca	Saldaña 1	Saldaña 2	Santa Teresa 1	Santa Teresa 2	Jarillas	Santa Isabel
Diameter (m)	1.60	1.77	1.55	1.75	2.05	1.60	1.56
Weight of wheel (t)	2.312	1.953	2.829	2.875	3.795	2.079	2.153
Largest pressure (kp/cm^2)	0.762	0.715	0.971	0.911	1.251	0.761	0.724
Angle of vertical axis (α^0)	5	16	1	8	3	5	4
Angle of horizontal axis (β^0)	2	5	4	3	1	2	3
Radial skidding (m)	0.019	0.044	0.041	0.030	0.044	0.019	0.028