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NUMERICAL SIMULATION OF MEZCAL PRODUCTION USING A SOLAR DISTILLER, COMPOUND PARABOLIC COLLECTORS (CPC'S) AND WATER AS WORKING FLUID

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Abstract: The distillation technique used to obtain mezcal consists of raising the temperature of a copper alembic, which contains cooked chunks of the heart of the agave -called "piña"- mixed with water, to a temperature in the range of 80 and 90 degrees Celsius. To reach these temperatures, the traditional technique uses the burning of logs of different species of trees and natural gas or LP gas, so, most of the heat source used is unsustainable. Here the simulation of a mezcal distiller using water which passes through a solar Compound Parabolic Concentrator truncated according to the Rincon's criterion [1] and a copper coil to heat the still is presented. Temperatures on the outside of the copper coil and inside the still of the system are presented in 3D simulations to show that using solar energy a controlled process can be achieved, much more sustainable that the one currently used to obtain the product. Finally, a schematic diagram of the process in frontal and isometric view is presented.
Keywords: Solar Mezcal distil, CPC`s, Heat transfer, Rincon´s Criterion, copper helicoidal, copper mezcal distiller

INTRODUCTION

Mezcal has its origin in the Nahuatl word "Mezcalli", which means "cooked maguey" (cooked agave). Between 2016 to 2018 its production increased; the different kinds of mezcal depend on the agave species, the distillation technique, and the climate, having the denomination of origin eight states of the country: Oaxaca, Zacatecas, Durango, Guanajuato, Guerrero, San Luis Potosí, Tamaulipas and Michoacan [2]. It is considered a distilled drink, piña-made brew. The process has five steps:

A) Shaving or "Jimado": Roughing off the leaves of the piña (the heart of the maguey).

B) Baking: The piña cut in chunks is baked in a ground oven, after which it is left to cool.

C) Crushing: When the chunks are cold, they are crushed; the traditional way is by the use of a rolling milling stone which is pushed by a horse around a circular trajectory.

D) Brew: The crushed chunks are placed in a container with water and left to ferment for about 12 days.

E) Distillation: The most important thermodynamics and heat transfer process happen in this step. In the traditional distillation, the producers heat a copper alembic still (with water and the fermented chunks inside) with fossil gas or logs to reach a temperature between 80 and 90° degrees Celsius, as shown in Figure 1. After this, the mixed of alcohol and water passes through a condenser to obtain mezcal distil.

The traditional distillers do not use clean sources of energy in the heating process and they don't even have thermometers to measure and control the temperature inside, so they might produce harmful sub-products called "puntas" and "colas" in the distillation process. These sub-products can cause severe ills or death to mezcal consumers. So, it is desirable to substitute fuels by the heating water processes, using only solar CPCs for this purpose in systems that guarantees a good temperature control, considering all the variables to be controlled in the proposed process.

Figure.1. Heating of the alembic by means of logs.

The solar mezcal distiller proposed by Cruz Martínez [3] employs a parabolic cylindrical concentrator, which is capable of reaching temperatures of up to 102 °C in 5 minutes. In conclusion, he proposes to measure thermal values in the future to control the temperature and implement optical tests, which is a viable technological alternative different from the one proposed in this article.

In the literature review, other types of solar distillers have been found; however, they are for purposes different from mezcal production, such as those mentioned by Melchor Quintas D [4]. For this reason, they are not mentioned in detail

METHODOLOGY

CPC'S DESIGN

The CPC's were designed around in 1970 [5], the finally objective consist to concentrate the sun trough static dispositive's, because all the ray's sun concentrate radiation in acceptation angle of the concentrator. The Rincon's criterion is useful to minimize material's and fabrication with a low cost. With a concentration factor of C=2, we obtain a semi-angle value of θ_c = 20.03 [°], with the equation:

$$C = \frac{1}{sen(\theta_c)} \tag{2.1}$$

And considering an evacuated tube with an external diameter of D_{ext} = 58 [*mm*], we obtain an aperture of *a* = 257.68 [mm], with the equation:

$$\theta_c = sen^{-1}\left(\frac{\pi . D_{ext}}{a}\right) \tag{2.2}$$

The equations to generate a CPC with optimal truncation are described in the following equations (equations 2.3, 2.4 and 2.5). The diagram in Figure 2 shows the evolvents in red, the macrofocal parabolas in blue and the evacuation tube with an external diameter of 58 [mm] in yellow.

$$\begin{matrix} x = r \cdot cos(\theta_o) \\ y = r \cdot sen(\theta_o) \end{matrix}; \; 0 \le t \le 2\pi \tag{2.3}$$

$$\begin{matrix} x(t) = r[sen(t) - t \cdot \cos(t)] \\ y(t) = -r[\cos(t) + t \cdot sen(t)] \end{matrix}; \; 0 \le t \le \frac{\pi}{2} + \theta_o \tag{2.4}$$

$$\begin{matrix} x(t) = r\left[\frac{sen(\theta_o) \cdot \cos(t - \theta_o) - \left(\frac{\pi}{2} + t + \theta_o\right) \cdot \cos(t)}{1 + sen(t - \theta_o)} + \cos(\theta_o)\right] \\ y(t) = -r\left[\frac{cos(\theta_o) \cdot \cos(t - \theta_o) + \left(\frac{\pi}{2} + t + \theta_o\right) \cdot \text{sen}(t)}{1 + sen(t - \theta_o)} - sen(\theta_o)\right] \end{matrix}; \tag{2.5}$$

$$\frac{\pi}{2} + \theta_o \le t \le \frac{3\pi}{2} - 3\theta_o$$

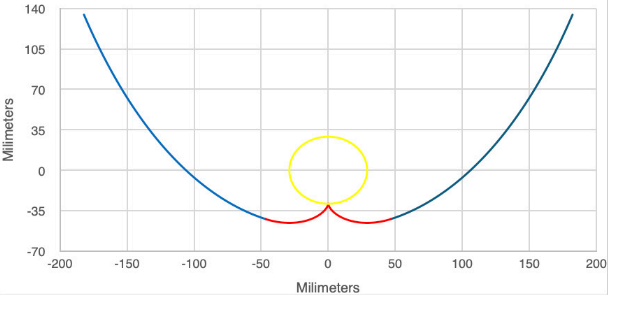

Figure.2. Rincón criterion for a CPC with a solar concentration of 2 (C=2)

For the prototype, the considered length of the evacuated tubes was 1.8 [m] long (which is the commercial available size), with an external diameter of 58 [mm] and an internal diameter of 47 [mm], in borosilicate glass material. Figure 3 shows the front view of the prototype of a channel with the evacuated tube and in Figure 4 the isometric view.

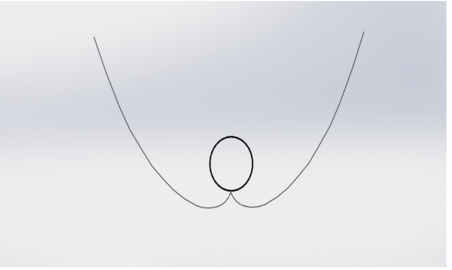

Figure.3. CPC canal with a evacuate tube, front view.

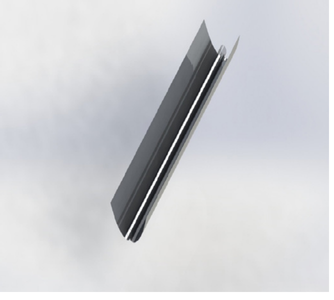

Figure.4. CPC with a evacuate tube, isometric view.

BRIEF THERMAL ANALYSIS AND NUMBER OF CPC'S

The thermal analysis was carried, with the purpose to know the number of concentrators (CPC`s) and evacuate tubes, necessary to elevate the temperature from 24.5 to 90 degrees Celsius. The values of Ambiental temperature, clarity index and irradiation were obtained in the National Aeronautics and Space Administration (NASA) web page [6] and using as coordinates the Universidad Tecnologica de los Valles Centrales de Oaxaca (latitude 16.801° and longitude -96.7993°).

The calculations of declination δ, hour angle ω_s, zenith angle θ_z and azimuth solar angle γ_s, were performed by means of calculations contained in the literature of Duffie and Beckman [7] and Kalogiru [8], and using the Perez anisotropic sky model [9] to determine the values of direct, diffuse and reflected radiation on an inclined surface (16.82°), obtaining values of 317.56, 182.16 and 2.04 $\frac{W}{m^2}$ respectively. The thermal efficiency is shown in equation 2.6 [10], which depends on the useful heat Q_u, absorber aperture area A_a and the average solar radiation over the inclined surface G_t and the optical efficiency [11] shown in equation 2.7, where the ω is the reflectance of the miro-sun® sheet, τ the glass transmissivity, α absorptivity and ϑ number of imperfections. The length L [12] of the tubes required for the process is shown in equation 2.8, where m is the mass flow rate, C_p specific heat of water, $T_{m,o}$ outlet temperature, $T_{m,i}$ average inlet temperature, d_i inner diameter of the evacuated tube and q_s total solar radiation.

Finally, the longitude of evacuated tubes for the process is shown in equation 2.9 [12].

$$\eta = \frac{Q_u}{A_a G_t} \tag{2.6}$$

$$\eta_{optical} = \omega\tau\alpha[1-\vartheta] \tag{2.7}$$

$$L = \frac{\dot{m}C_p(T_{m,o} - T_{m,i})}{\pi \cdot d_i \cdot \dot{q}_s} \tag{2.8}$$

$$\#L_{tubes} = \frac{L}{\eta \cdot \eta_{optical}} \tag{2.9}$$

COPPER HELICOIDAL HEAT TRANSFER

The average input temperature in the copper helicoidal is $T_{m,i}$ = 88°, the superficial temperature outside the copper helicoidal must be between T_s = 80 to 90°, for that reason the chosen temperature of T_s = 358.15 K (average between 353.15 to 363.15 K), with this guarantees an optimal distill process. Based in the functional prototype of Mezcal Bravero located in the Mexican state of Oaxaca and with 6 steps of the copper helicoidal (N = 6), around the alembic, the characteristics of the alembic and the copper helicoidal are shown in Figure 4 and in Table 1

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Figure 4. Copper helicoidal and alembic.

Characteristic	Value
Alembic diameter	0.67434 [m]
Alembic high	0.840 [m]
Extern diameter of the copper tube	0.0667 [m]
Intern diameter of the copper tube	0.0642 [m]
Helicoidal steps number	6 [steps]

Table 1. Characteristics of the helicoidal and alembic.

The proposed mass flow values of minimum are $\dot{m}_{min} = 0.02 \left[\frac{kg}{s}\right]$ and maximum $\dot{m}_{max} = 2.6 \left[\frac{kg}{s}\right]$, using water properties tables the cinematic viscosity was obteined $\mu = 343 \times 10^{-6} \left[\frac{N \cdot s}{m^2}\right]$, the Reynolds number calculation is shown in equation 2.10 [12].

$$Re_{spiral-alembic} = \frac{4\dot{m}_{espiral-cobre}}{(\pi)\left(D_{ext_{tub-Cu}}\right)(\mu)} \quad (2.10)$$

Based on previously obtained values, the correlations to obtain the friction factor inside the copper helicoidal were known, for this reason there are a valid correlation of Reynolds numbers due Petukhov, between , Prandtl numbers between and the friction factor was calculated by the equation 2.11 [10], this was necessary to obtain the Nusselet number through the equation 2.12 [12], the convection coefficient and the outside temperature was calculating by the equations 2.13 and 2.14 [12].

$$f = \left[0.79 ln\left(Re_{esp-almb}\right) - 1.64\right]^{-2} \quad (2.11)$$

$$Nu_{esp-almb} = \frac{\left(f/_8\right)\left(Re_{esp-almb} - 1000\right)Pr}{1 + 12.7\left(f/_8\right)^{1/2}\left(Pr^{2/3} - 1\right)} \quad (2.12)$$

The Prandtl number at the aforementioned temperature has a value of Pr=1.9324 and the thermal conductivity coefficient has a value of k=0.6762.

$$\bar{h} = \frac{\left(\frac{f}{8}\right)\left(Re_D - 1000\right) \cdot P_r \cdot k}{\left[1 + 12.7\left(f/_8\right)^{1/2}\left(Pr^{2/3} - 1\right)\right] \cdot D} \quad (2.13)$$

$$T_{m,o} = T_s - \left[exp^{\left(-PL\bar{h}/\dot{m}C_p\right)}\right]\left[T_s - T_{m,i}\right] \quad (2.14)$$

The perimeter of the alembic was obtained with the diameter P=πD=π·0.67434m=2.1185m and the tube equivalent longitude by equation 2.15 [12].

$$L_{tube} = \frac{\pi D_{alembic}}{N} = \frac{\pi(0.67434[m])}{6} = 0.3530\,[m] \quad (2.15)$$

The specific heat was obtained at the average inlet and outlet temperature of the copper helicoidal, which has a value of 361.107 , and by means of water properties tables we obtain a specific heat value of $C_p = 4205.92 \left[\frac{J}{kgK}\right]$. With all the above, the outlet temperature of the copper helicoidal was calculated by equation 2.16 and the mass flow with by equation 2.17 [12].

$$T_{m,o} = T_s - \left[exp^{\left(-PL\bar{h}/\dot{m}C_p\right)}\right]\left[T_s - T_{m,i}\right] \quad (2.16)$$

$$\dot{Q} = \dot{m}C_p\left(T_{m,o} - T_s\right) \quad (2.17)$$

RESULTS

To obtain the length of the evacuated tubes, the thermal efficiency was first obtained with a value of useful energy gained in the CPC's of Q_u=*225.1W*, absorber aperture area A_a=*0.4637m²* and an average radiation on a sloping surface of $G_t = 595.8054 \left[\frac{W}{m^2}\right]$. Obtaining a value of $\eta = \frac{225.1\,[W]}{(0.4637\,[m^2])\left(595.8054\left[\frac{W}{m^2}\right]\right)} \approx 0.8147 \approx$ 81.47%, which is high due to the use of the Rincon criterion.

For the calculation of the optical efficiency, a reflectance of the miro-sun sheet with a value of ω=0.85, which corresponds to the intermediate value between 80 and 90 %, a transmissivity of τ=0.92, an absorptivity of α=0.92, and a proposed number of imperfections of ϑ=0.15 were used. Obtaining a value of $\eta_{optical}$=0.85*0.92[1-0,15]≈0.6115≈61.15%.

The necessary length of the evacuated tubes to raise the temperature from $T_{m,i}$=297.619 K, which corresponds to the average temperatures obtained from 2015 to 2019 through the NASA website, to an outlet temperature of the CPCs of $T_{m,o}$=363.15K, with a proposed mass flow of m=0,01 $\frac{kg}{s}$, specific heat obtained from tables of C_p=4184.2 $\frac{kJ}{kgK}$, internal tube diameter of and the total surface irradiance obtained above, we have a length of

$$L = \frac{\left(0.01\frac{kg}{s}\right)\left(4184.2\frac{J}{kgK}\right)(363.15-297.619)K}{\pi(0.047\ m)\left(595.8054\frac{W}{m^2}\right)} \approx 31.16\ m$$

Dividing this value by the thermal and optical efficiency we obtain the final pipe length $L_f = \frac{31.16\ m}{0.8147*0.6115}$=62.54$m$, finally dividing the obtained value by the length of each evacuated tube we need $\#Tubes = \frac{62.54\ m}{1.8\ m} \approx$ 34.74≈35 evacuated tubes with CPC's to guarantee the desired temperature.

Using the methodology described in section 2.3, Table 2 shows the results for the different mass flow rates selected Reynolds numbers, friction factor, Nusselet number, convection coefficient, outlet temperature, and power transferred to the copper alembic. In Figure 5 and Figure 6 the mass flow vs. outlet temperature of the copper helicoidal and mass flow vs. power transferred to the copper still are shown, with this we can guarantee an optimal distill.

Mass Flow $\left[\frac{kg}{s}\right]$	Reynolds number [*dimensiones*]	f [*dimensiones*]	Nu [*dimensiones*]	$h\left[\frac{W}{m^2K}\right]$	$T_{m,o}$ [K]	Q [W]
0.02	1111.5642	0.0325	0.6069	6.1055	361.1	1.3510
0.05	2778.9105	0.0254	7.8485	78.9560	361.0	17.2769
0.1	5557.8210	0.0215	17.4011	175.0554	361.0	38.2478
0.15	8336.7314	0.0196	25.8603	260.1543	361.0	56.8491
0.2	11115.6420	0.0184	33.7555	339.5800	361.0	74.2289
0.25	13894.5525	0.0176	41.2820	415.2959	361.0	90.8089
0.3	16673.4630	0.0169	48.5391	488.3027	361.0	106.8039
1.925	106988.0540	0.0119	240.7328	2421.7656	361.0	531.4175
2.575	143113.8910	0.0113	308.7710	3106.2274	361.0	681.9208

Table 2. Mass flow, Reynolds number, friction factor, Nusselet number, convection coefficient, outlet temperature and power transfer to the copper tube.

Simulations were performed to better observe the temperature distribution in the copper still, for this purpose a mass flow of , was used, at this value the power transferred from the copper helicoidal to the still is , in Figure 7 an isometric view is show, in Figure 8 a top view and finally in Figure 9 a side view.

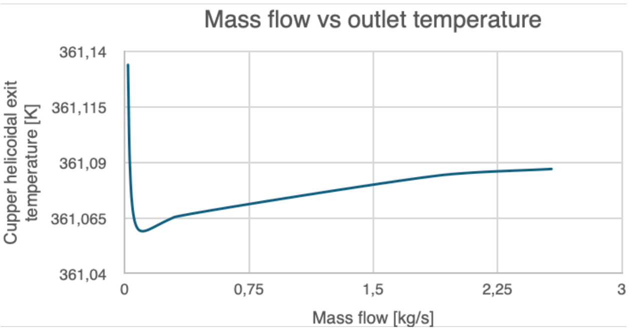

Figure 5. Mass flow vs. outlet temperature.

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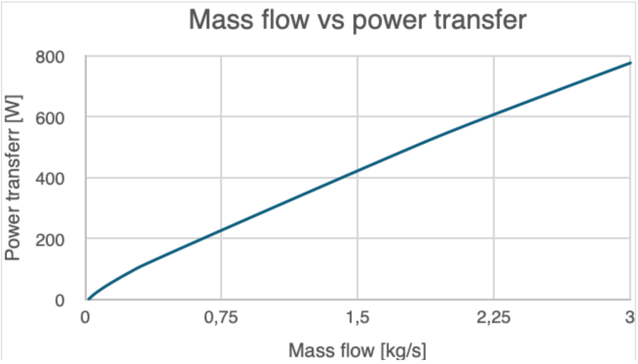

Figure 6. Mass flow vs. power transfer.

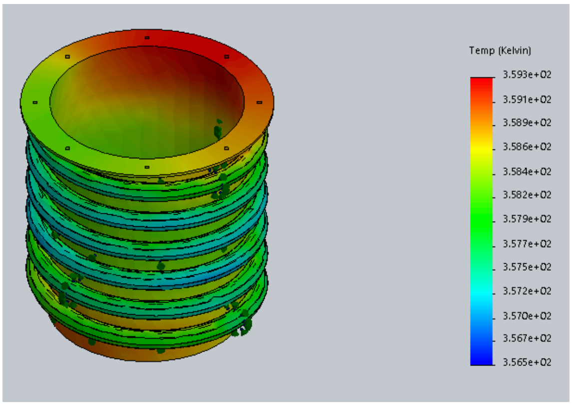

Figure 7. Isometric view of temperature distribution in copper alembic in Kelvins.

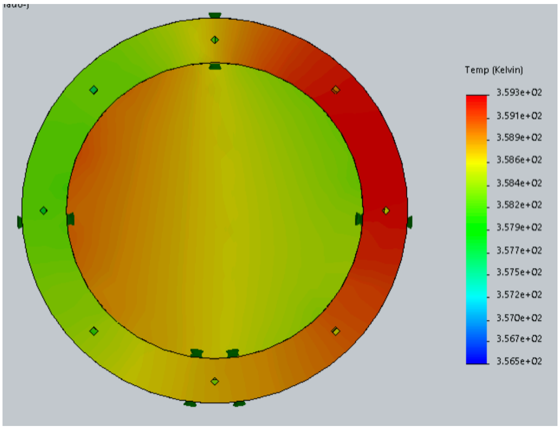

Figure 8. Top view of temperature distribution in copper alembic in Kelvins.

Finally, Figure 9, shows the complete scheme of the process and the Figure 10 an isometric view.

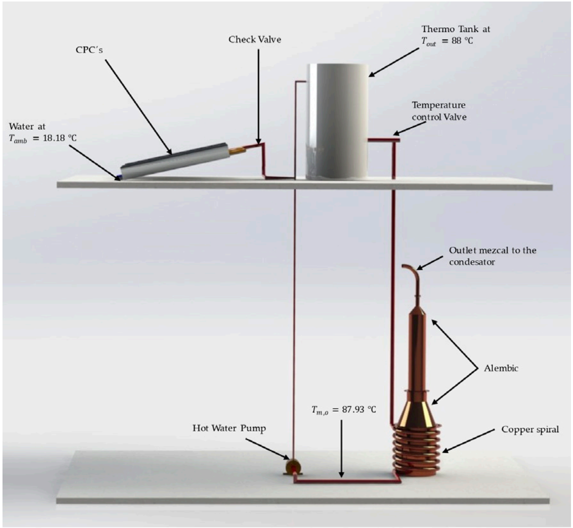

Figure 9. Scheme of the process.

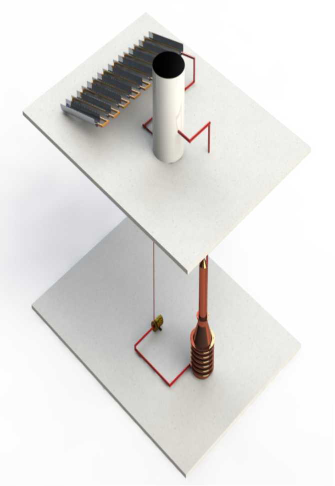

Figure 10. Isometric view.

CONCLUSION

A numerical analysis of a solar device for the production of mezcal in a copper alembic still was presented, however any distilled beverage requires the same degrees of temperature, so this study can be extended to any elaboration of these that need to go through a similar process. Taking into account the materials and dimensions of the alembic, which can be made of steel, the conductivity parameters of the material must be taken into account.

Water was used as the working fluid, because in the state of Oaxaca in Mexico, the population is accustomed to using this fluid in the condensation part to obtain the beverage.

To employ the same methodology, the solar radiation at the study site and the geographical location must be taken into account, and from this, calculate how many CPC's using Rincon's criteria, with evacuated tubes, are necessary to achieve this end, the size of the still and the litres of beverage to be distilled, which is feasible to adapt the current distillation systems in order to have a lower impact on CO2 emissions to the atmosphere and to ensure a green and low carbon industry for the production of similar products.

The bottom of the alembic should be insulated to ensure proper temperature distribution.

The mass flow of water at the inlet of the helicoidal should have a value of 2.575 [kg/s], to transfer a heat power to the still of Q=681.2[W] and thus avoid putting another pump at the outlet of the storage tank, for which the recommended height is 5 meters, from the entrance of the copper helicoidal upwards.

The proposal guarantees the elimination of the "puntas" and "colas" during the distillation process, which are harmful to health.

The components have a useful life of 20 years, i.e. the product can be distilled without the need to consume non-renewable energy sources and a maintenance that only involves conventional cleaning.

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