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ENTROPY GENERATION CALCULATIONS DURING PARCHMENT COFFEE DEHYDRATION PROCESSES FOR A TRADITIONAL OPEN ROTARY DRUM DYER AND HARC^{2}S CONFIGURATIONS

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Abstract— **Entropy generation during parchment coffee dehydration processes was calculated for two specific thermodynamic cycles, namely, open rotary drum dyer and a HARC^{2}S configuration. It was observed that open rotary drum dyer entropy generation was very high and chaotic as compared to the HARC^{2}S configuration thermodynamic cycle. The HARC^{2}S exhibited a well behaved quasi steady state linear behavior. A figure-of-merit, N_s, was used to directly compare the entropy generation of the open rotary drum dyer to that of HARC^{2}S. It was observed that for the entire dehydration processes the N_s ranged from a minimal of 0.1678 to a maximum of 5.4407 with an average of 4.4051, clearly indicating that the entropy generation of the open rotary drum dyer was always higher. Based on these results it is observed that the entropy generation of the HARC^{2}S configuration is much lower and thus provides a higher quality dehydration process by reducing thermodynamic cycle irreversibility. In this study it is observed that the benefits of using a HARC^{2}S configuration for parchment coffee dehydration not only provides a highly energy efficient thermodynamic cycle but also provides a higher heating quality as compared to the traditional open rotary drum dyer.**

Keywords— **Entropy Generation, Parchment Coffee, Dehydration, Energy Efficiency**

I. NOMENCLATURE

C_{P_c}	Parchment coffee beans specific heat, (kJ/kg-K)
$h_{1,2}$	Moist-air specific enthalpy, (kJ/kg$_a$)
$\dot{m}$	Moist-air mass flow rate, (kg/s)
$\dot{m}_a$	Dry air mass flow rate, (kg$_a$/s)
N_s	Entropy comparison figure-of-merit
P_v	Water vapor pressure, (kPa)
$\dot{Q}$	Heat transfer rate, (W)
S	Total entropy, (kJ/K)
$\dot{S}_{gen}$	Total entropy generation rate, (W/K)
s	Specific entropy, (kJ/kg-K)
s_w	Liquid water specific entropy within parchment coffee bean, (kJ/kg-K)
$s_{1,2}$	Moist air specific entropy, (kJ/kg-K)
T_c	Parchment coffee beans bulk temperature, (K)
t	Time, (s)
W_c	Ratio of water content in parchment coffee bean mass to moist-air mass flow rates, (s).
$W_{1,2}$	Humidity ratio, (kg$_v$/kg$_a$)

II. INTRODUCTION

The high and increasing costs associated with propane gas, diesel and electricity used by mechanical dryers have negatively affected the coffee processors industry in Puerto Rico. From all the sectors within the coffee industry in Puerto Rico, the processors are the ones that have experience the largest increases in operational cost of over 145%, mainly due to post harvesting drying [1].

To address this specific challenge, the Department of Agriculture of Puerto Rico (DAPR) assigned funds to research coffee dehydration energy efficient alternatives that would reduce the costs to the coffee processors of the island [2]. As part of this effort, a *Hot Air Recirculation Controlled Closed System* (HARC^{2}S) was designed and constructed at the University of Puerto Rico, Mayagüez Campus. The basic concept of the HARC^{2}S is to condition the hot air that has already passed through the coffee beans and direct it back to the mechanical dryer. The conditioning of the hot air consists in removing part of the moisture from the recirculation air with an air-water type Heat Exchanger (HX) that uses water at ambient temperature, to increase the moisture absorbing capacity of the air before it re-enters the mechanical dryer [3].

The traditional open rotary drum dyer used for parchment coffee beans drying in Puerto Rico is highly energy inefficient, exposes the coffee bean to non-uniform drying temperatures and non-uniform moisture content wet-base (M.C. (w.b.)) distribution within the coffee beans. This problem forces the coffee processors to retain the parchment coffee beans in the open rotary drum dyer for longer periods of times to ensure the desired M.C. (w.b.) of 10%-12% is reached, consuming more energy. A more serious problem associated with the traditional open rotary drum dyer is the possibility of contamination due to direct ambient exposure. The nature of the contamination can range from foreign objects ending up in the coffee beans, to potential fungal and bacteria growth [4-9]. This is a challenge that the coffee processors face on their day-to-day operations during the drying season of coffee harvesting, which for Puerto Rico is between the months of August to January.

The HARC^{2}S was developed to address the issues of energy inefficiencies of the traditional open rotary drum dyer. After its construction, parametric thermodynamic models where developed. The details of the construction, its energy savings, and the parametric thermodynamic models are contained in the references [3, 10]. The parchment coffee beans entering and leaving hot moist air dry-bulb temperatures and relative humidity measurement were used as an essential component of calculating the entropy generation for the two configurations, namely: opened batea which corresponds to open rotary drum dyer and closed batea which correspond to HARC^{2}S configuration. The parchment coffee beans bulk temperature and M.C. (w.b.) during the dehydration process was continuously monitored. The entering and leaving hot moist air dry-bulb temperatures and relative humidity were also monitored, while keeping the environmental integrity of the HARC^{2}S during the drying cycle. The integrity is maintained by not opening the HARC^{2}S until the desired M.C. (w.b.) of 10% to 12% is reached. Keeping the environmental integrity of the HARC^{2}S during dehydration cycles has the following advantages: (1) quasi-adiabatic environment is maintained providing an energy efficient system, (2) minimize and/or eliminates contamination to the coffee from foreign objects, (3) minimize the potential of bacterial and fungal growth. Therefore, using the HARC^{2}S has the potential to ensure coffee bean safety and quality.

III. Materials and Methods

The energy efficient HARC^{2}S was designed, constructed, and located at the University of Puerto Rico at Mayagüez for parchment coffee dehydration [3]. Please refer to Figure 1. The dehydration process takes place in a chamber where hot air is forced through the organic material in a closed air loop. The hot and humid air passing through the parchment coffee material is directed to a HX device where a portion of the moist air water content will be condensed and collected outside the dehydration cycle with minimum recirculating hot air temperature drop. The dehumidified air will recirculate back into the heating source where it will be heated back to the dehydration temperature setting of the system. Energy conservation is possible due to the small temperature drop experienced

Figure 1: Photographs of the parchment coffee dehydration prototype systems. **Left**: open rotary drum dyer referred to as the opened-batea (OB) configuration. **Right**: HARC^{2}S referred to as the closed-batea (CB) configuration. The top middle component is the HX that removes dehydration water from the thermodynamic cycle.

by the air when entering and leaving the HX. Thus, the required energy from the heating source is much smaller as compared to the open system currently being used by the coffee processors, which always need to continuously heat air at ambient temperature. The HX device uses water at ambient temperatures (20 to 32°C) to condense part of the water vapor from the recirculating air, creating minimum temperature drop. An added system benefit of using water at ambient temperature is that the only energy required for the HX operation is from a small circulating centrifugal water pump. The amount of pump energy usage is relatively small when compared to other commercial HX devices, which uses air conditioning equipment that requires a vapor-compression cycles. Water at ambient temperature was used for all the closed-system experiments. However, other liquids or gases can be used with minimum energy requirement. To further reduce the thermal energy losses to the ambient, ¾" insulation (FLEX USA) was used to provide a near adiabatic closed-system environment.

The HARC^{2}S was instrumented to monitor moist air dry-bulb temperatures and relative humidity throughout the system at sample rates of one reading per minute with HOBO Pro V2 (U23-002) temperature and relative humidity sensors. Also, HOBO Pro V2 (U23- 003) temperature sensors were located within the coffee beans and were set to collect data at a sample rate of once per minute. Although the HOBO sensors were set to collect data rates of once per minute, after evaluation of the collected data, ten minutes interval data was used in the analysis. This was done since there were no significant changes observed on a minute-to-minute basis. Parchment coffee beans samples of 2 oz. were collected at sample rates interval of once per hour.

The parchment coffee bean samples were used to measure the M.C. (w.b.) with a calibrated Denver Instrument IR-35 Moisture Analyzer. All the HOBO sensors were synchronized to collect and perform data logging simultaneously. The focus was placed on the energy and mass transfer dynamics surrounding the parchment coffee beans during a dehydration cycle. The parameters of particular interest are the experimentally measured dry-bulb temperatures and relative humidity of the hot moist air entering and leaving the parchment coffee beans, measurements of coffee beans bulk temperature, and M.C. (w.b.).

The thermal physical properties of the hot moist air entering and leaving the coffee beans are calculated using the measured dry-bulb temperature, relative humidity, and barometric pressure. It was observed that the thermal physical properties are continually changing during the dehydration cycle in the HARC^{2}S, especially the hot moist air leaving the parchment coffee beans.

IV. Entropy Generation Analysis

The second law of thermodynamics is an excellent analysis tool that provides information as to the quality of any thermodynamic process and allows quantification of irreversibility in the form of entropy generation [11-13]. In this case quality is referred to the availability of useful heat energy for the purpose parchment coffee dehydration. The general entropy balance equation (1) was adjusted to the specific case of the parchment coffee chamber depicted in figure (2).

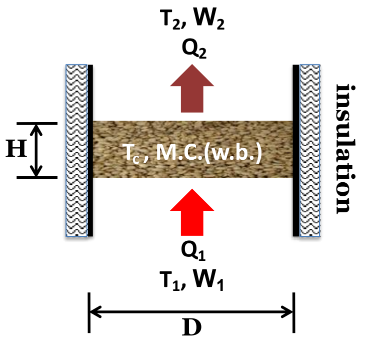

Figure 2: Depiction of parchment coffee dehydration chamber with location of measured parameters.

$$\frac{dS}{dt} = \sum_{i} \frac{\dot{Q}_i}{T_i} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \dot{S}_{gen} \tag{1}$$

The availability of useful heating energy for the dehydration process is achieved by adjusting equipment parameters such as volumetric air flow rates, input air temperatures, among others, with the purpose of reducing $\dot{S}_{gen}$. The specific equation for the case of figure 2 and used for this study is given by,

$$\frac{\dot{S}_{gen}}{\dot{m}_a} = s_w(W_1 - W_2) + W_c\frac{ds_w}{dt} - \frac{\dot{Q}/\dot{m}_a}{T_c} - (s_1 - s_2) \tag{2}$$

Please refer to the nomenclature table for specific definitions of the variables of equation (2). The heat transfer parameter, $\dot{Q}$, of equation (2) is derived from the first law of thermodynamics and is presented in equation (3) in its final form.

$$\dot{Q}/\dot{m}_a = C_{P_c}T_c(W_1 - W_2) + W_C T_c \frac{dC_{P_c}}{dt} + W_C C_{P_c}\frac{dT_c}{dt} - W_c(h_1 - h_2) \tag{3}$$

To establish entropy generation comparisons between the two types of dehydration thermodynamic processes, namely: opened batea (OB) and closed batea (CB) a figure-of-merit, N_s, as presented in equation (4) was used.

$$N_s = \frac{(\dot{S}_{gen})_{OB}}{(\dot{S}_{gen})_{CB}} \tag{4}$$

The N_s parameter used, $(\dot{S}_{gen})_{OB}$ and $(\dot{S}_{gen})_{CB}$represent the cumulative entropy generation for the OB and CB configurations. The results of N_s, as well as, other parameters of interest were plotted against dehydration process times, total parchment coffee mass bulk temperature, water vapor pressure, and coffee mass moisture content wet-based.

V. Methodology

Parchment coffee beans dehydration experiments were conducted using the HARC^{2}S in a closed air recirculation mode. The HARC^{2}S was instrumented with dry-bulb temperature and relative humidity sensors, HOBO Pro V2 (U23-002), located at the air entering and leaving the coffee beans. The temperature and relative humidity sensors made measurements at sample rates of 1 reading per minute. Also, the hot air temperature thermostat was set and maintained at 55ºC using a 2.5 kW electric make-up air heater (EM-WX0212R) with a warm flow controller from Electro Industries, Inc. The airflow rate was set to be in the range of 90 to 100 CFM.

The coffee during the drying process was completely isolated from external ambient conditions and was continually turned over at a rate of 2 rpm by means of a mechanical rotating arm with rakes. The hot humid air that passed through the parchment coffee beans was directed to the conditioning HX to reduce its moisture content with minimum temperature drop and then redirected back to the heating source to increase its temperature to the desired setting. Please refer to Figure 1.

Temperature sensors, HOBO Pro V2 (U23-003), were placed within the coffee beans and measurements were taken at a rate of 1 sample per minutes. Furthermore, an initial parchment coffee bean sample was taken and its M.C. (w.b.) was measured. Subsequences samples were collected at sample rates of one per hour to determine their M.C. (w.b.) using a calibrated Denver Instrument IR-35 Moisture Analyzer. The parchment coffee beans were dehydrated until the M.C. (w.b.) reached the limit of less than 12%, which is the threshold to insure protection of the grain for transport and subsequent storage. The average final M.C. (w.b.) of the samples for all the experiments was 11.71%. The hot moist air dry-bulb temperatures and relative humidity reading, and barometric pressure were used to calculate the thermal physical properties of the hot air entering and leaving the coffee beans.

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VI. RESULTS AND DISCUSSION

Using the collected experimental data as outlined, calculations of entropy generation using equation (2) for the two dehydration processes were performed. MATLAB scripts were specifically developed for calculating the thermal-physical properties of the moist air as a function of measured dry-bulb temperature, relative humidity, and barometric pressure. Furthermore, the parchment coffee mass specific heat as a function of measured M.C. (w.b.) was also calculated with MATLAB. Finally, the entropy generation as presented in equation (2) as calculated using a MATLAB script. Refer to the references [3,10] for details on all collected measured data.

Water vapor pressure is a very important thermodynamic parameter during parchment coffee dehydration processes. During dehydration the water vapor pressure within the coffee mass should be higher than the water vapor pressure of the surrounding air such that a pressure gradient is created away from the coffee mass, inducing water migration away from the coffee mass. Application of controlled heat to the coffee mass, the water within the coffee mass changes phase from liquid-to-vapor in a controlled gradual manner, and thus leaves the coffee due to pressure gradient driving forces.

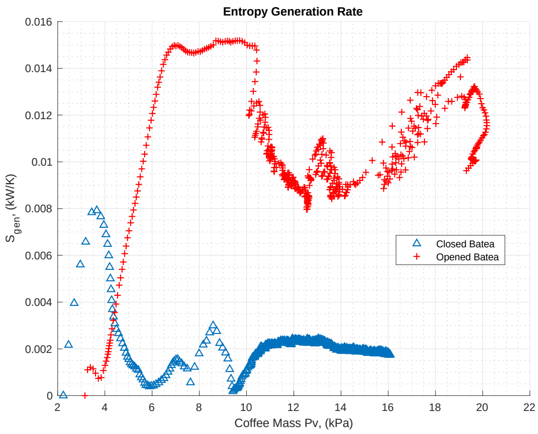

Figure 3: Depiction of instantaneous entropy generation vs. parchment coffee mass water vapor pressure for both dehydration processes in the OB and CB configuration.

Figure 3 depicts the instantaneous entropy generation of both dehydration processes. Notice how the entropy generation for the case of OB is much higher and chaotic when compared to the CB. For the case of CB, the entropy generation appeared to reach a quasi-steady state behavior which was not observed in the OB.

The entropy generation during dehydration process time was monitored and the cumulative entropy generation N_s was plotted against M.C. (w.b.), time, and coffee mass heat absorption. Please refer to figure (4).

Notice how the entropy generation for the OB is much higher and exhibits a highly chaotic behavior when compared to the CB. Based on the N_s the dehydration process cumulative entropy generation was always higher for the OB ranging from a minimum of 0.1678 to a maximum of 5.4407, averaging over the entire dehydration period to be 4.4051.

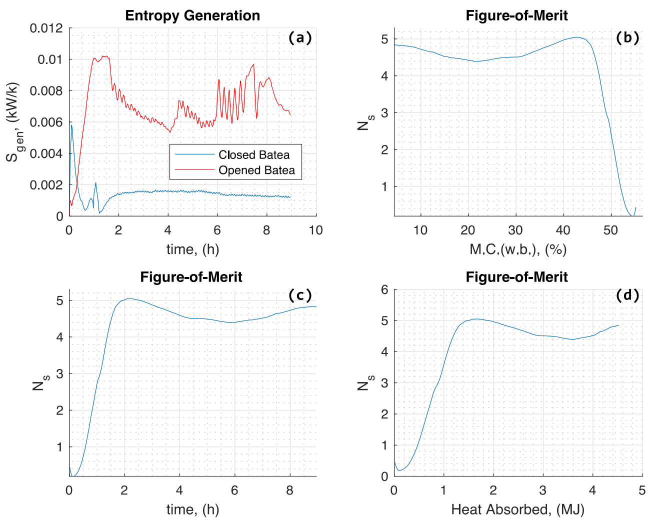

Figure 4: Depiction of entropy generation and N_s comparisons. (a) Instantaneous entropy generation vs. dehydration time, notice how the OB is highly chaotic compared to the CB. The CB configuration after about 1.75 hours of dehydration appears to be well behaved in a linear manner. (b) N_s vs. M.C. (w.b.). (c) N_s vs. dehydration time. (d) N_s vs. coffee mass heat absorption. Notice how the N_s is always greater than zero, indicating that OB entropy generation is always higher in the CB configuration.

In figure (5), the cumulative entropy production is plotted against coffee mass water content during the entire dehydration cycle for both configurations. In this plot it is very evident that the cumulative entropy production for the OB is always much higher than that of the CB configuration.

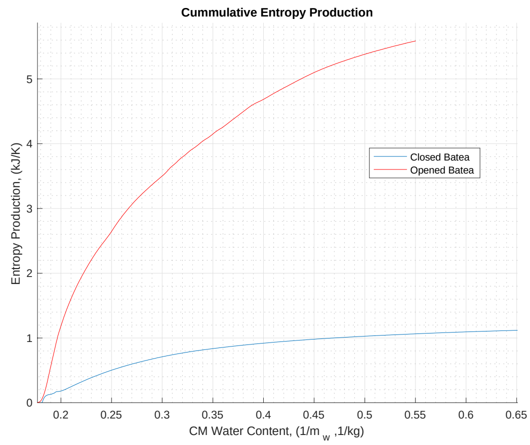

Figure 5: Depiction of cumulative entropy production vs. parchment coffee mass water content during entire dehydration cycle.

The HARC^{2}S CB configuration is known to be energy efficient [3] and mathematical model to predict coffee mass moisture content and coffee mass temperature during entire dehydration process time have been developed [10]. However, taking a new look at this process from a second law of thermodynamic perspective, specifically entropy generation during the dehydration processes for the cases of OB and CB configurations, gives us another view in terms of the quality of the energy used during dehydration and the impact this has on the overall energy efficiency of the dehydration process.

VII. CONCLUSION

Entropy generation for parchment coffee dehydration processes have been calculated. It was observed that the entropy generation was large and highly chaotic for the case of OB configuration. The parchment coffee mass in the OB is always in direct thermal communication with the ambient moist air fluctuations. On the other hand, the CB entropy generation exhibited a quasi-steady state linear behavior. In the CB configuration, the parchment coffee mass in not in direct thermal contact with the ambient air, but rather it is in direct thermal contact with a thermally controlled environment. The heat-treated conditioned air, once exposed to the coffee mass, is redirected to a heat-exchanger which removes a high percentage of the water extracted from the coffee mass, thus reducing the overall latent load of the air. Afterwards, the air is once again redirected back to the coffee mass with a higher sensible load quality, that is a lower humidity ratio.

Given the nature of the $HARC^2S$ impact on the thermal quality of the conditioned air, it has a direct impact on minimizing entropy generation during parchment coffee dehydration. Thus, the second law of thermodynamics provides direct insight to the quality of the useful heat being used, which in this study can clearly be seen that the $HARC^2S$ is not only highly energy efficient during dehydration cycles but provides excellent useful heating qualities as compared to the open batea configuration.

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