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Application of an Energy Efficient Hot Air Recirculation Controlled Closed System Environment for Parchment Coffee Dehydration in Puerto Rico

Francisco Rodríguez-Robles[1,2], Francisco M. Monroig-Saltar[3], David Serrano-Acevedo[2]

ABSTRACT

The high and increasing costs associated with propane gas, diesel and electricity used by mechanical dryers have negatively affected the coffee processors in Puerto Rico. In 1991 the cost to process one hundred pounds of parchment coffee was $14.13, while in 2011 was over $35.00. 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, over 145% in the past years, mainly due to post harvesting drying. 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. 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 at Mayagüez. The basic concept of the HARC^{2}S is to condition the hot air that has already passed through the coffee bean mass and direct it back to the mechanical dryer. The hot air conditioning consist in removing part of the moisture from the recirculation air with a heat exchanger that uses water at ambient temperature, to increase the moisture absorbing capacity of the air before it re-enters the mechanical dryer. Experimental results of the HARC^{2}S, under various operational configurations, provided substantial drying energy savings ranging from 12% to 59%. The range variation in energy savings is due to the system operational configurations and possible variations of the parchment coffee bean ripeness state from the various batch experiments. Investing in the development and implementation of this technology will provide not only sustainable operation of the coffee processors facilities, but will also sustain close to 20,000 jobs with potential employment growth representing over a $41 million annual income to the local economy.

Keywords: Coffee, Drying, Energy, Parchment, Air-Recirculation

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INTRODUCTION

The coffee industry remains among the top ten agricultural businesses in order of economic importance in Puerto Rico. Coffee harvesting contributions are highly important to the local economy of the central zone of the island's population [1]. However, with increasing production and processing cost growing at a faster rate than the regulated price, which have not been revised since 2005, this agriculture sector faces many challenges. Among the top factors that have negatively affected the coffee processors are the high-energy costs of the parchment coffee dehydration process.

There are around 4,094 coffee producers and 199 coffee processors in the island. The vast majorities are small to medium size farmers distributed in 22 municipalities within the central-western region of the island. The coffee industry provides about 20,000 direct and indirect jobs in a region with high unemployment rate. Furthermore, there are 58 coffee roasting companies with over 100 commercial brands. The majority, are small to medium size businesses that process specialty coffees. During the past decade, specialty high quality coffee roasting companies have increase from 18 in the year 2000 to 58 in 2012, reflecting a significant increase of 222% in this agriculture sector. The main reason for the increase in this sector can be attributed to a DAPR regulation that permits the sale of specialty coffee at a higher price than commercial coffee. This regulation allows the coffee processor to become a roster and take advantage of higher selling prices to cover its production costs and increase revenue. There is a need to increase the production and processing of this high quality coffee bean in order to meet the market demand and be able to sell the product at higher prices according to this regulation.

The island coffee production in the 2010- 2011 coffee harvest season was 120,000 quintals (1 quintal = 100 lbs.), with an average market value of $29.5 M [19]. In 2008, the coffee industry in Puerto Rico generated 15% of the total agricultural crops gross income. However, the fact that the value of coffee production has increased does not mean that yields have increased. The value increase is attained by an increased in product price due to other factors, such as, high processing energy costs.

The global coffee industry in 2012 generated nearly $30B according to the International Coffee Organization. Puerto Rico has the potential to be a key contributor in this market due to its tropical climate and altitudes, presenting ideal environmental conditions to produce one of the world finest quality coffee beans. However, due to parchment coffee bean high drying operational energy cost, the ability to become a true global competitor is hindered. The development of an energy- efficient dehydration machinery will provide to this agriculture sector not only top quality coffee, but will also sustain close to 20,000 jobs with potential employment growth representing over a $41 million [2] annual income to the local economy.

In 2011, the DAPR understanding the needs of the coffee industry, funded several research projects related to energy conservation in parchment coffee drying [3]. As part of this effort, the design and construction of a of an energy efficient hot air recirculation controlled closed-system (HARC^{2}S) environment scaled-prototype for parchment coffee dehydration was conducted at the University of Puerto Rico at Mayagüez. The main objective of the HARC^{2}S is to dehydrate parchment coffee with minimum energy consumption without negatively affecting the coffee bean quality.

Figure 1: Depiction of a typical rotary drum drier (batea) used in Puerto Rico to dehydrate parchment coffee (*C. arabica*). This particular batea was instrumented to collect coffee mass and air data *in situ* for typical drying cycles.

Typical mechanical coffee dryers in Puerto Rico are the fixed-bed and rotary silos with airflow inversion, and the rotary drum driers known as "*bateas*". Mechanical dryers available to the coffee processors use fossil fuel to heat ambient air that is forced through the parchment coffee layer and then released to the environment (open-systems) as shown in Figure 1. The amount of energy consumed during a parchment coffee dehydration cycle in an open-system is as follows: 87%-91% of energy is consumed from fossil fuel and 9%-13% is consumed from other auxiliary equipment such as rotating arm mechanism electric motor, air fan and combustor fan.

The high and increasing costs associated with propane gas, diesel and electric consumption of the mechanical dryers have negatively affected the coffee processors. In 1991 the cost to process one hundred pounds of coffee was $14.13, while in 2011 was over $35.00. Of all the sectors of the coffee industry in Puerto Rico, the coffee processors are the ones that have experienced the largest increases in cost, over 145% in the past years [1].

The current standard for dry parchment coffee commercialization establishes a wet based (w.b.) moisture content (M.C.) of 10% to 12% [4] of the beans as the appropriate parameter for storage and handling conditions. If the coffee beans M.C. are greater than 13%, this will cause a considerable deterioration of the beans since it will be prone to a moldy appearance and stains from fungus attacks [5]. The presence of certain fungus (*Aspergillus ochraceus*) may have serious health risks, since this fungus is known to be a producer of a toxin (*Ochratoxin A.*) that have teratogenic, immunotoxic, neurotoxic, and possible carcinogenic properties [6-11]. To avoid damaging or killing the coffee germ and ruining the potential flavor of coffee during the dehydration process, the beans temperature must not surpass 50°C [4], although some literature suggest that the maximum allowable temperature should not exceed 45°C [5].

Previous researchers have studied the effect of hot-air temperature, airflow, bed depth, and air flow reversal for parchment and natural coffee dehydration for systems with no air recirculation [12-16]. Mathematical simulations and recommendations for various commercial coffee dryers have been performed for those systems [15]. The National Coffee Research Center of Colombia (CENICAFÉ by its Spanish initials) has also studied the various coffee dehydration systems with no air recirculation [4]. Little or no reference is made to parchment coffee (*C. arabica*) dehydration using an integrated $HARC^2S$ as the one presented in this research effort.

The integrated $HARC^2S$ has the potential to considerably reduce dehydration energy consumption as compared to the open-systems currently used by coffee processors. Recirculating and reconditioning the warm air that passed through the coffee beans with minimum temperature drop will require less energy from the heating source. The conditioner removes the return air excess humidity increasing its water carrying capacity.

A study using only 30% of hot-air recirculation for drying hay reported energy savings of 27% at fall and 17% at summer [16]. Another study reported that air recycling means energy savings of 21% to 38.5% in a rotary dryer for vegetable wholesale by-products [17,18]. The coffee harvesting and processing season is at fall and coincides with a heavy rain period at the tropic. A closed-system is expected to provide additional benefits because the coffee will be isolated from the environment, minimizing possible negative influences of ambient conditions to the bean dehydration process, allowing not only control of the bean drying, but maintaining bean quality.

MATERIALS AND METHODS

An energy-efficient HARC^{2}S was designed and constructed at the University of Puerto Rico at Mayagüez for parchment coffee dehydration, please refer to Figure 2.

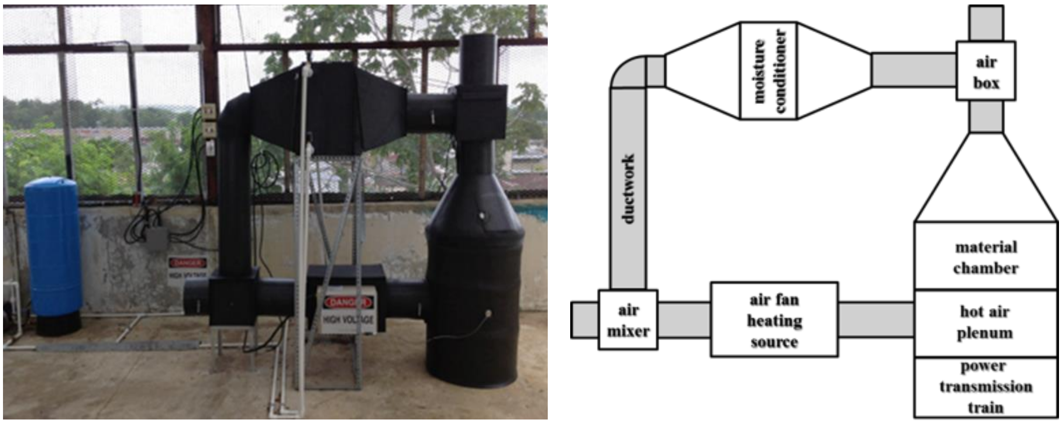


Figure 2: Depiction of the HARC^{2}S located at the University of Puerto Rico at Mayagüez. (a) Side-view picture of the dehydration system. (b) Sketch of the system with identification of the major components.

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 that passes through the parchment coffee material is directed to a heat exchanger (HX) device where a portion of its water content will be condensed and collected outside the dehydration cycle with minimum recirculating hot air temperature drop. The conditioned (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 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 that uses air at ambient temperature.

The HX device using water at ambient temperatures (20 to 32°C) is used to condense part of the water vapor from the recirculating air, creating a minimum temperature drop. An added system benefit of using water at ambient temperature is that the only energy required for the HX operation is for the centrifugal pump that circulates the water. The amount of energy is relatively small when compared to other commercial HX devices, which uses some kind of air conditioning equipment that requires a compressor. 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 reduce the energy loss through the system, the dehydration device and auxiliary components are insulated with a ¾" (K-FLEX USA) to provide a near adiabatic closed-system environment.

CONSTRUCTION DESIGN DETAILS

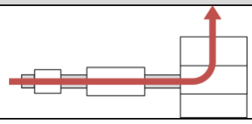
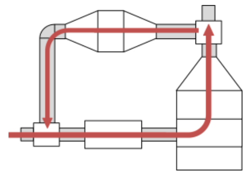
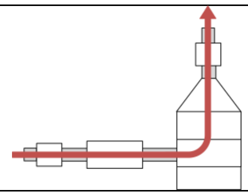
The HARC^{2}S has been tested with Puerto Rico parchment coffee (*C. arabica*) beans from freshly picked coffee. The HARC^{2}S has five (5) major components as shown in Figure 2b, namely: (1) material dehydration chamber with a rotating arm mechanism, (2) heating source with fan, (3) moisture conditioning heat exchanger, (4) air recirculation ductwork, and (5) conditioning fluid reservoir.

a. *Material Dehydration Chamber*: The material dehydration chamber consist of three sections; namely, (1) the material chamber with a perforated floor to allow controlled hot air passage and a mixing device for even dehydration, (2) the hot air plenum were the hot air enters and is directed into the material chamber, and (3) the power transmission train chamber were the mechanisms for the mixing device rotating shaft are located.
b. *Air Fan and Heating Source*: The heating source used for the experiments was an electric resistor instrumented to measure the energy consumption. However, this source can be substituted for fossil fueled based heating, renewable energy based, and/or other. A duct fan with a flow control was used to direct the air from the mixer to the heating source.
c. *Moisture Conditioning Heat Exchanger*: The recirculating hot air with high humidity leaving the material dehydration chamber passes through the moisture conditioning heat exchanger where part of the air water content is removed. The air exits the HX with lower moisture content and with minimum temperature drop, and is directed back to the heating source. The air recirculation is maintained until the desired material moisture content is reached.
d. *Ductwork*: The ductwork interconnects the entire system recirculating pathways.
e. *Fluid Reservoir:* The fluid reservoir stores water at ambient temperature, which is below the hot recirculating air's dew-point temperature. Other fluids may be used to condense the recirculating air moisture, as long as they do not require large amounts of energy to do their function.

METHODOLOGY

A series of experiments were conducted at various HARC^{2}S settings in order to determine the system performance under different conditions as shown in Table 1. Specifically three configurations were evaluated: open, semi-open, and closed. For all the configurations the hot air temperature was set to 50ºC using a 2.5 kW electric make-up air heater (EM-WX0212R) with warm flow controller from Electro Industries, Inc. The airflow rate was set to be in the range of 90 to 100 CFM.

Table 1: HARC²S experimental configurations tested.

Experiment	Description	Diagram
OB-1	Open configuration. Loaded with 10 kg of washed parchment coffee. Mixing mechanism rotating at a rate of 2 rpm. Base comparison	
CB-1	Closed configuration. Loaded with 10 kg of washed parchment coffee. Mixing mechanism turned-over once every 30 minutes.	
CB-2 & CB-3	Closed configuration. Loaded with 10 kg of washed parchment coffee. Mixing mechanism rotating at a rate of 2 rpm.	
SCB-1	Semi-closed configuration. Loaded with 10 kg of washed parchment coffee. Mixing mechanism rotating at a rate of 2 rpm.	

The configuration OB-1, open-system, was set to emulate the existing parchment coffee rotary-drum dryers used by coffee processors of the island. Outside air was heated and passed through the parchment coffee mass only once and then discharged into the environment. The coffee mass was continuously turned-over via a rotating arm with a mixing mechanism at a rate of 2 rpm. The energy consumption from this particular configuration was used to establish the baseline for comparison.

The configuration CB-1, closed-system, was completely isolated from the ambient and the coffee mass was turned-over only once every 30 minutes. Configurations CB-2 and CB-3, closed-system, were also completely isolated from the ambient but the coffee mass was continually turned-over at a rate of 2 rpm. The last configuration tested was SCB-1, semi-closed system, where the coffee mass was isolated from the ambient but no hot air recirculation was used. For SCB-1 the outside air was heated and passed through the parchment coffee at the dehydration chamber and then discharged to the environment with no recirculation. The difference between SCB-1 and OB-1, both discharging directly to the environment with no hot air reconditioning, is that for OB-1 the parchment coffee beans were in direct contact with the environment, whereas in SCB-1 they were isolated. For CB-1, CB-2, and CB-3 configurations, the hot humid air that passed through the parchment coffee mass 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.

All experiments started with an open system configuration for the first hour to discard the excess moisture from the parchment coffee. After the first hour, the closed and semi-closed systems were installed. The parchment coffee beans were dehydrated until the moisture content (MC) of about 12% (w.b.) was reached. The average final moisture content of the samples for all the experiments was 11.71% (w.b.). Small parchment coffee samples were taken every hour to determine their MC using a Denver Instrument IR-35 Moisture Analyzer.

The energy consumption (E_c) was continually measured using a watt node 208/240 VAC 3-phase delta/wye kWh transducer sensor (T-WNB-3D-240) and recorded at a sample rate of 1 reading/min using a HOBO UX120 pulse data logger.

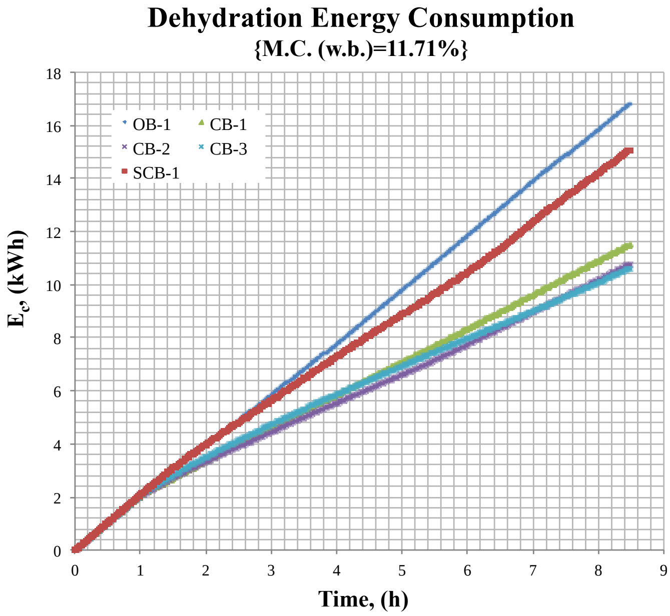


Figure 3: Depiction of the HARC^{2}S dehydration cumulative energy consumption continually measured using a watt node 208/240 VAC 3-phase delta/wye kWh transducer-sensor (T-WNB-3D-240) and recorded with a HOBO (UX120) pulse data logger.

RESULTS AND DISCUSSION

The drying time for all the HARC^{2}S configurations evaluated in the experiment was about 8.5 hours for an original parchment coffee mass of 10 kg. This suggest that the drying time to reduce the moisture content of parchment coffee from about 56% to 12% was not affected by the system configurations considered. However, the energy consumption in the closed configurations was significantly less when compared to the open configuration. Figure 3 shows the cumulative dehydration energy consumption (E_c) variation with time. The dehydration energy consumption was the same for all configurations for the first hour since they all started as an open system. Once the ductwork was in place for the closed-systems and the HX started conditioning the redirected air, the energy savings become evident instantly. The semi-closed system started showing energy savings after the third hour and was significantly less than the closed systems.

Using the open system configuration as a basis for comparison, the energy consumption savings were 46.28% for CB-1, 56.17% for CB-2, 58.73% for CB-3 and 11.79% for SCB-1. For the experiments OB-1 and CB-1 the parchment coffee was harvested on a different date than for experiments CB-2, SCB-1, and CB-3. The slight difference in the amount of saved dehydration energy between CB-2 and CB-3 can be attributed to a variation in the parchment coffee sample composition, i.e. ripeness degree. Furthermore, experiments CB-2 and CB-3 clearly demonstrate the dehydration energy consumption stability of the $HARC^2S$. The dehydration energy saving of CB-1 was lower than those of CB-2 and SCB-1 because the mixing mechanism arm was rotated once every 30 minutes instead of rotating at 2 rpm, as in the case of the other experiments.

The coffee bean quality was not evaluated for these experiments; the effort was centered mainly on energy conservation. However, coffee quality is of pivotal importance, because improper drying can lead to the generation of mycotoxins produced from fungus infestation, and inappropriate dehydration temperatures can affect flavor. This parameter will be researched in subsequent work.

CONCLUSIONS

The concept of a hot air recirculation controlled closed-system environment for parchment coffee dehydration have proven, based on the experimental results, to have the potential to be an effective dehydration process to reduce the energy consumption at coffee processing facilities, especially for the tropical climate of Puerto Rico. The experimental results obtained, indicate that the dehydration energy reduction using the proposed closed system is substantial, ranging in the order of 12% for the semi-closed system and up to 59% for the closed-system, as compared to the traditional open-system environment. The incorporation of a $HARC^2S$, as seen from the experimental results, has far reaching benefits for the coffee industry in Puerto Rico. The potential implementation of this technology can be directly translated into the creation of sustainable and competitive coffee processors.

An additional benefit of the closed-system lays in the ability to control the quality of the parchment coffee during the dehydration cycle. The closed-system provides a controlled near adiabatic drying environmental state, which is isolated from ambient conditions, eliminating possible contamination and/or drying climate variations that will negatively impact quality, as well as, increase drying cost due to ambient variations.

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