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Parametric Thermodynamic Models of Parchment Coffee Beans during HARC²S Dehydration

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Abstract

Parametric thermodynamic models have been developed to predict the temperature and moisture content wet base (M.C. (w.b.)) of parchment coffee beans during dehydration process in a hot air recirculation controlled-closed system (HARC²S). The principals of energy and mass transfer conservation during dehydration are the basis of the models. Experimental data of the moist air dry-bulb temperatures, relative humidity, and barometric pressure of the air entering and leaving the coffee beans are used to calculate the air thermal physical properties. These properties are used in the temperature prediction model. The coffee mass aspect ratio as determined by the HARC²S organic material chamber, predicted temperature, water-coffee effective diffusivity coefficient, and initial measured moisture content are required in the M.C. (w.b.) model.

The experimental temperature data profile behavior appeared to be of a lumped-capacitance nature, while the M.C. (w.b.) experimental data had a linear constant rate decent behavior during dehydration. The linear decent appears to be an inherent characteristic property of the HARC²S dehydration process. The models prediction average errors as compared to the experimental data were, ± 1.8803% error for the temperature, and ± 1.8599% error for the M.C. (w.b.).

The coffee processors will directly benefit from the developed thermodynamic models. They will have the capacity to continually monitor the parchment coffee beans temperature and M.C. (w.b.), while keeping the environmental integrity of the HARC²S during dehydration processes. The integrity is maintained by not opening the HARC²S until the desired M.C. (w.b.) of 10% to 12% is reached. Maintaining the environmental integrity of the HARC²S has the following advantages: (1) system energy efficiency is maintained within quasi-adiabatic environment; (2) coffee contamination from foreign objects is eliminated; (3) potential of bacterial and/or fungal growth are minimized. Thus, using the HARC²S has the potential benefit of insuring coffee bean safety and quality.

Keywords: Parametric model; Dehydration; Coffee bean

Nomenclature

$\dot{E}_{in}$ - Parchment coffee beans entering energy rate, (kW)

$\dot{E}_{out}$ - Parchment coffee beans leaving energy rate, (kW)

$\dot{Q}$ - Parchment coffee beans stored energy rate, (kW)

$\dot{Q}$ - Air flow rate entering and leaving parchment coffee beans, (m³/s)

ρ_{SA} - Entering hot moist air density, (kg/m³)

$\bar{\rho}_{SA}$ - Entering average hot moist air density, (kg/m³)

ρ_{RA} - Leaving hot moist air density, (kg/m³)

ρ_{bulk} - Parchment coffee bulk density, (kg/m³)

$C_{P_{SA}}$ - Entering hot moist air specific heat, (kJ/kg-K)

$\bar{C}_{P_{SA}}$ - Entering average hot moist air specific heat, (kJ/kg-K)

$C_{P_{RA}}$ - Leaving hot moist air specific heat, (kJ/kg-K)

CP- Parchment coffee specific heat, (kJ/kg-K)

W_{SA}- Entering hot moist air humidity ratio, (kg/kg)

W_{RA}- Leaving hot moist air humidity ratio, (kg/kg)

T_{SA}- Entering hot moist air temperature, (˚C)

T_{RA}- Leaving hot moist air temperature, (˚C)

T_c- Parchment coffee beans temperature, (˚C)

T - Temperature, (˚C)

V_{bulk}- Parchment coffee beans bulk volume, (kg/m³)

M- Parchment coffee beans wet base moisture content, (M.C. (w.b.))

M_i- Initial parchment coffee beans wet base moisture content, (M.C. (w.b.))

h_g- Water vapor enthalpy (kJ/kg)

h_{fg}- Water liquid-vapor phase change enthalpy (kJ/kg)

t- Time (s)

ϵ- Parchment coffee beans macro porosity

C_1- Coefficient, (kJ/K)

C_2- Coefficient, (kW)

C_3- Coefficient, (kW/K)

C_4- Coefficient, (kW)

ϕ_1- Coefficient, (kW)

ϕ_2- Coefficient, (kW)

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u_0- Initial condition coefficient, (K/s)

D- HARC²S organic material chamber diameter, (m)

D_{eff}- Effective diffusivity, (m^2/s)

k_m- Moisture transport coefficient, (1/s)

C- Parchment coffee beans geometric characteristic

M_C - Adjustment coefficient factor, (1.1556 kg/kg)

Introduction

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 [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 HARC²S was designed and constructed at the University of Puerto Rico at Mayagüez. The basic concept of the HARC²S is to condition the hot air that has already passed through the coffee bean and direct it back to the mechanical dryer. The conditioning of the hot air consist 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 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 insure 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 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 HARC²S was developed to address the issues of energy inefficiencies of the traditional open rotary drum dyer. After its construction, the authors identified the need for the development of thermodynamic models, which can be used during drying processes. The thermodynamic models will allow the prediction of parchment coffee beans temperature and M.C. (w.b.) during typical dehydration process cycles. The parchment coffee beans entering and leaving hot moist air dry-bulb temperatures and relative humidity measurement will be used as an essential component of these thermodynamic models. The coffee processors will have the capacity to monitor the parchment coffee beans temperature and M.C. (w.b.) at all times during the dehydration process. The entering and leaving hot moist air dry-bulb temperatures and relative humidity are recommended be used due to the ease of measurement of this type of data, while keeping the environmental integrity of the HARC²S during the drying cycle. The integrity is maintained by not opening the HARC²S until the desired M.C. (w.b.) of 10% to 12% is reached. Keeping the environmental integrity of the HARC²S 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 of foreign objects, (3) minimize the potential of bacterial and fungal growth. Therefore, using the HARC²S has the potential to insure coffee bean safety and quality.

Materials and Methods

The energy-efficient HARC²S designed and constructed by the authors is 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

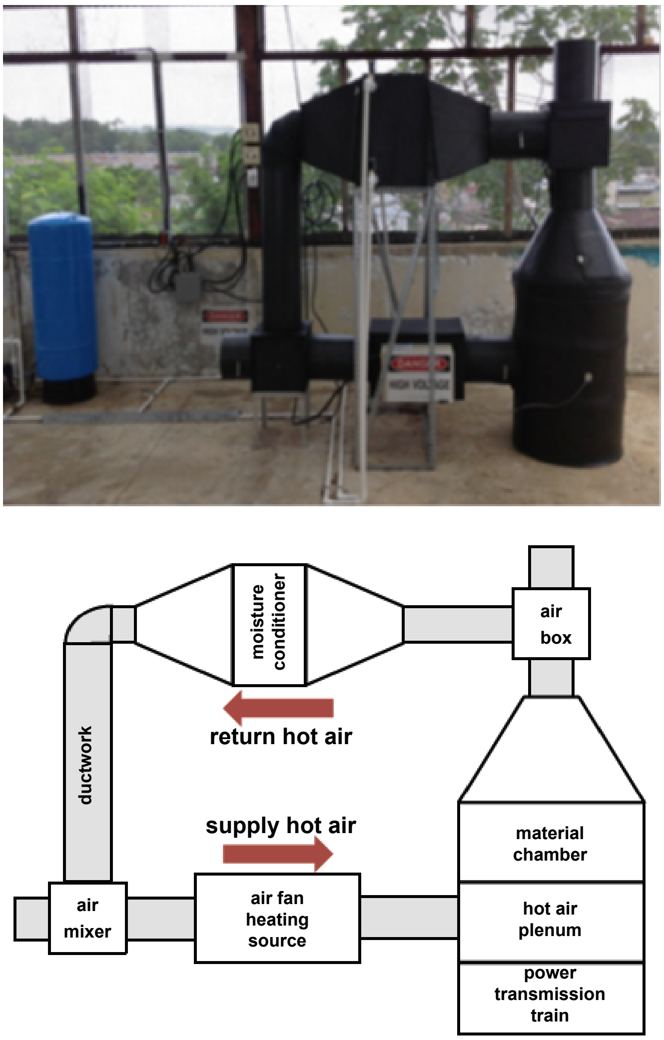

Figure 1: Depiction of the HARC²S located at the University of Puerto Rico at Mayagüez. (a) Side-view picture of the dehydration system. (b) Sketch of the system with identification of the major components.

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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 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 uses 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 centrifugal pump that circulates the water. The amount of energy usage is relatively small when compared to other commercial HX devices, which uses some kind of air conditioning equipment that requires a vapor-compression cycle. 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 thermal energy losses to the ambient, the system dehydration¾" device(K and auxiliary components are insulated with a - FLEX USA) insulator to provide a near adiabatic closed-system environment.

The HARC²S 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 a 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.

These 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 authors focused their attention to 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 temperature, and M.C. (w.b.) measurements during dehydration cycles. Please refer to Figure 2.

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 HARC²S, specially the hot moist air leaving the parchment coffee beans.

Parametric Thermodynamic Models

Parchment coffee beans temperature and M.C. (w.b.) prediction parametric thermodynamic models were developed for typical dehydration processes in the HARC²S based on the energy and mass transfer conservation principals. The thermal physical properties of hot moist air such as, specific heats ($C_{P_{SA}}$ and $C_{P_{RA}}$) and densities (ρ_{SA} and ρ_{RA}), were calculated using experimentally collected dry-bulb temperatures, relative humidity, and barometric pressure. The calculation methodology proposed by Tsilingiris [10] was used to determine these parameters. Parchment coffee thermal physical properties (C_P and ρ_{bulk}) and the macro porosity (ε) were calculated based on parchment coffee beans experimentally measured data M.C. (w.b.) in conjunction with the thermal properties of parchment coffee beans reported by Pérez-Alegría et.al. [11].

The fundamental governing equations for parchment coffee beans temperature predictions must account for sensible and latent energy. The energy and mass transfer balance is given by:

$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} \quad (1)$$

where,

$$\dot{E}_{in} = \dot{Q}\rho_{SA}C\rho_{SA}\left(T_{SA} - T\right) \quad (2)$$

$$\dot{E}_{out} = \dot{Q}\rho_{RA}C\rho_{RA}\left(T - T_{RA}\right) + \dot{Q}\left[\rho_{RA}W_{RA} - \rho_{SA}W_{SA}\right]h_g \quad (3)$$

$$\dot{E}_{st} = \frac{\rho_{bulk}C_pV_{bulk}}{1-\varepsilon}\frac{dT}{dt} + \left[\frac{\rho_{bulk}V_{bulk}}{1-\varepsilon}\right]\frac{dM}{dt}h_{fg} \quad (4)$$

Notice that Equation (2), the energy entering the coffee beans, is mainly sensible in nature, while Equation (3), energy leaving the coffee beans is sensible and latent in nature. The energy being stored within the coffee beans, Equation (4) is sensible and latent in nature. Substitution of Equations (2) through (4) into Equation (1) yields Equation (5), a coupled sensible and latent energy expression for parchment coffee beans thermodynamic behavior; temperature and M.C. (w.b.). Equation (5) is valid during typical dehydration processes within the HARC²S.

$$\frac{\rho_{bulk}C_pV_{bulk}}{1-\varepsilon}\frac{dT}{dt} + \left[\frac{\rho_{bulk}V_{bulk}}{1-\varepsilon}\right]\frac{dM}{dt}h_{fg} = \dot{Q}\rho_{SA}C_{p_{SA}}\left(T_{SA} - T\right) \quad (5)$$

$$-\dot{Q}\rho_{RA}C_{p_{RA}}\left(T - T_{RA}\right) - \dot{Q}\left[\rho_{RA}W_{RA} - \rho_{SA}W_{SA}\right]h_g$$

Of particular interest in solving Equation (5), is the determination of the parchment coffee beans temperature (T = Tc), which has an analytical solution given by,

$$T_c = \frac{C_4}{C_3} - u_0\frac{C_1}{C_3}\exp\left(-\frac{C_3}{C_1}t\right) \quad (6)$$

Where,

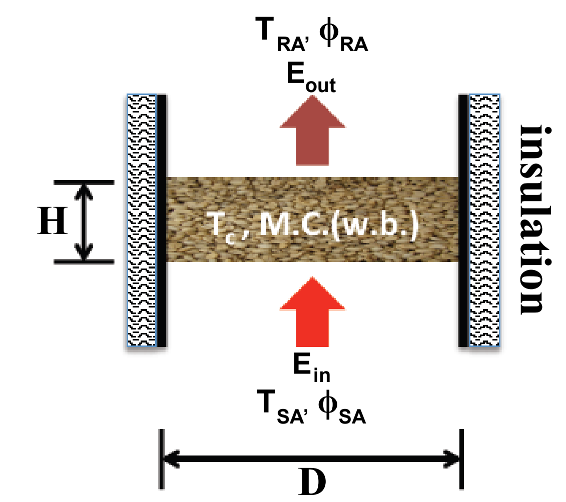

Figure 2: Depiction of parchment coffee beans within the organic material chamber HARC²S.

$$C_1 = \frac{\rho_{bulk} C_p V_{bulk}}{1-\varepsilon} \tag{7}$$

$$C_2 = \dot{Q}\left(\bar{\rho}_{SA} \bar{C}_{P_{SA}} T_{SA_{\max}} + \rho_{RA} C_{P_{RA}} T_{RA}\right) \tag{8}$$

$$C_3 = \dot{Q}\left(\bar{\rho}_{SA} \bar{C}_{P_{SA}} + \rho_{RA} C_{P_{RA}}\right) \tag{9}$$

$$C_4 = C_2 - \varphi_1 - \varphi_2 \tag{10}$$

$$\varphi_1 = \left[\frac{\rho_{bulk} V_{bulk}}{1-\varepsilon} \frac{dM}{dt}\right] h_{fg} \tag{11}$$

$$\varphi_2 = \dot{Q}\left(\rho_{RA} W_{RA} - \rho_{SA} W_{SA}\right) h_g \tag{12}$$

$$u_0 = -\frac{C_3}{C_1} T_i + \frac{C_4}{C_1} \tag{13}$$

Notice that Equations (8) and (9) are using the entering hot moist air average specific heat ($\bar{C}_{P_{SA}}$) and density ($\bar{\rho}_{SA}$). The average values are used since the heat source is a constant energy nature. Therefore, the variation in inlet dry-bulb temperature and relative humidity for the most part remains constant. However, the hot moist air leaving the parchment coffee beans specific heat ($C_{P_{RA}}$), density (ρ_{RA}), humidity ratio (W_{RA}), as well as, bulk coffee specific heat (C_p), bulk coffee density (ρ_{bulk}) are changing during the dehydration of the coffee beans. This change is attributed to the water leaving the parchment coffee beans during dehydration. The thermal physical properties are changing over time and must be calculated for each time interval. Thus, an expression that will predict parchment coffee beans temperature during a drying cycle has been developed and is being proposed, Equation 6.

Furthermore, notice that Equations (5) and (11) have the term dM/dt, implying that the parchment coffee beans moisture content is coupled to the coffee beans temperature. During typical drying cycle processes in the HARC²S, it is observed from experimental measurements that the parchment coffee beans dehydration dynamics behave in a near-linear manner, suggesting that dM/dt remained nearly constant during dehydration. Based on this observation, the rate change of M.C. (w.b.) during dehydration for the coffee beans was proposed by the authors to have the following form,

$$\frac{dM}{dt} = -\frac{k_m}{C} M_c \tag{14}$$

Equation 14, has the form of a Lewis model [12] with the difference that dM/dt in this case is assumed to be constant. The parameter km is a moisture transport coefficient, C is non-dimensional geometric characteristic parameters govern by the HARC²S organic material chamber, and Mc is an adjustment coefficient factor. The km and C parameters are given in Equations (15) and (16), respectively.

$$k_m = \frac{\pi^2 D_{eff}}{D^2} \tag{15}$$

$$C = \frac{H}{2D} \tag{16}$$

The parameter D_{eff} presented in Equation (15) is known as the effective diffusivity coefficient of parchment coffee, which has been published in the literature [13] and adopted here and is given by,

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \tag{17}$$

where, for the parchment coffee (C. arabica) beans, based on experimental data according to Corrêa [13] D0 = 2.041x10-6 m^2/s is the pre-exponential adjusted Arrhenius coefficient factor, Ea = 22.619 kJ/mol is the water activation energy, and T is the coffee beans absolute temperature. In Equation (16), H and D are the parchment coffee mass height (thickness) and diameter, determined by the HARC²S material chamber. Please refer to Figure 2. From Equation (14), it can be seen that,

$$\int_{M_i}^{M} dM = -\left(\frac{k_m}{C}\right) M_c \int_0^t dt \tag{18}$$

Solving Equation (18) and substituting Equations (15) and (16) into the solution will yield,

$$M = -\left(\frac{k_m}{C}\right) M_c t + M_i \tag{19}$$

Equation (19) provides an expression that will allow the prediction the parchment coffee beans M.C. (w.b.) dynamics during a typical dehydration cycle within the HARC²S.

Two expressions have been developed and are proposed be used by the coffee processors to predict parchment coffee beans temperature, Equation (6), and M.C. (w.b.), Equation (19), during dehydration process cycles in the HARC²S. The use of these expressions will avoid opening the system during drying processes, conserving the system environmental integrity.

Methodology

Parchment coffee beans dehydration experiments were conducted using the HARC²S in a closed air recirculation mode. The HARC²S 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(b).

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

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physical properties of the hot air entering and leaving the coffee beans. These thermal physical properties, as discussed in the Parametric Thermodynamic Models section, are the moist air specific heats (C_{pSA} and C_{pRA}), densities (ρ_{SA} and ρ_{RA}), and humidity ratios (W_{SA} and W_{RA}). Parchment coffee beans thermal physical properties variation as a function of M.C. (w.b.) for Puerto Rico coffee (*C. arabica*) has been published [11] and adapted here. These properties are the coffee bean bulk density (ρ_{bulk}), specific heat (C_p), and coffee mass porosity (ε). The water enthalpies (hfg and hg) were fitted from steam tables as a function of temperature [14]. Once all the thermal physical parameters were calculated, they were used in Equations 6-13 to calculate the parchment coffee beans temperature, which in turn were used with Equations 17 and 19 to calculate the M.C. (w.b).

Results and Discussion

The thermodynamic models predicted well the temperature and M.C. (w.b.) dynamics of the coffee during drying. Please refer to Figures 3 and 4. The thermal physical properties of the hot moist air and parchment coffee beans were calculated based on measured air dry-bulb temperature, relative humidity, and barometric pressure, while the coffee thermal physical properties were calculated on the basis of the M.C. (w.b.). The importance of determining these properties for each experimentally collected measurement is based on the transient nature of the coffee beans during drying.

The coffee beans thermal equilibrium state is changing with time due to the amount of water content that is leaving in the form of vapor during the dehydration process within the HARC²S. It is important to indicate that the proposed models assume the parchment coffee beans temperature is uniform throughout the dehydration process, similar to a lump-capacitance type.

The authors used a lumped-capacitance approach approximation based on observation of the experimental data. However, the authors are aware that the coffee mass energy distribution is not entirely uniformed during the dehydration cycle. The continuous coffee beans mechanical turn over from the rotating arms with rakes at a rate of 2 rpm allowed for a near uniform temperature distribution. The average Biot (B_i) numbers for coffee beans, and entering and leaving hot moist air were 3.641 and 3.596, respectively. Theses B_i number values are much greater than 0.01, which is the traditional value used to justify a lumped-capacitance method of solution. It is observed that there is an

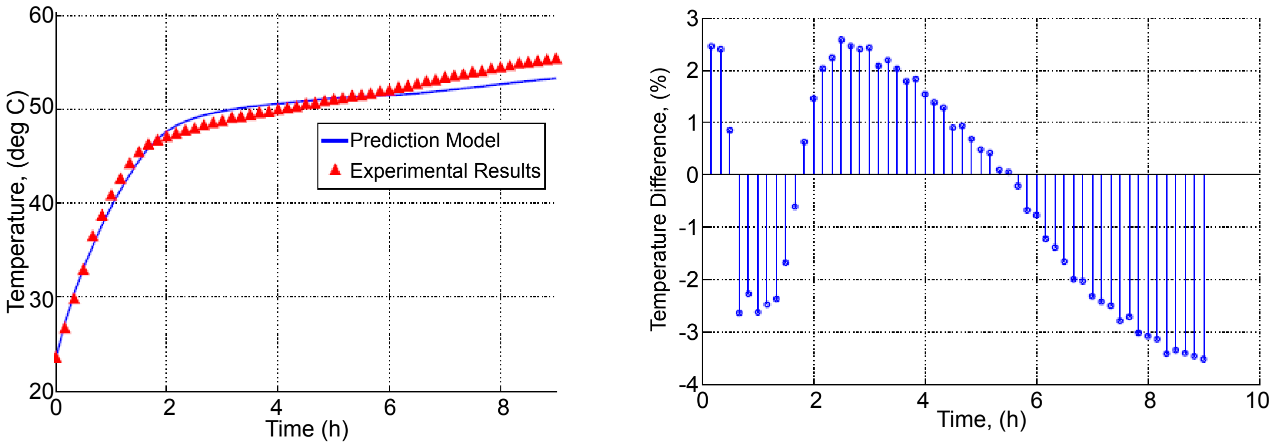

Figure 3: (a) Depiction of parchment coffee beans temperature profiles of prediction model and experimental collected data during dehydration process in the HARC²S. The RMSD = 0.50813 for the temperature comparison suggest a nicely fit prediction. (b) Plot of the temperature percentage difference comparison of the prediction model to the measured data with an average error of ± 1.8803%.

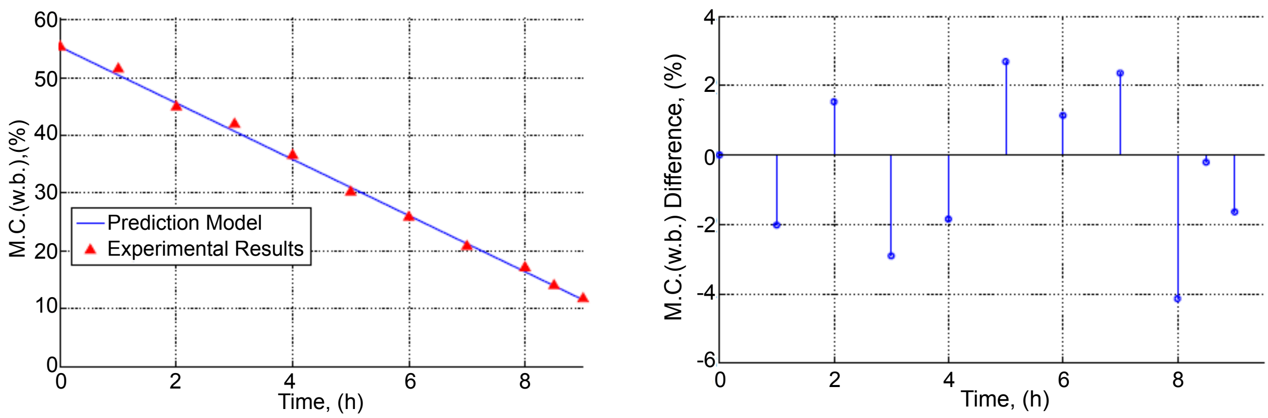

Figure 4: Depiction of parchment coffee beans M.C. (w.b.) profiles of prediction model and experimental collected data during dehydration process in the HARC²S. The RMSD = 0.16907 for the M.C. (w.b.) comparison suggest a nicely fit prediction. (b) Plot of M.C. (w.b.) percentage difference comparison of the prediction model to the measured data with an average error of ± 1.8599%.

increasing temperature gradient in the direction of entering hot moist air. Even though the Bi numbers calculated are much greater than the 0.01 threshold recommended for using the lumped-capacitance method, the temperature predicted with the model is in excellent agreement with the experimentally measured data. This gradient is small enough that the assumption of uniform temperature distribution is valid and justified based on the Root-Mean Squared Difference (RMSD) obtained from the coffee beans temperature predictions as compared to the measured data. In this case RMSD = 0.50813.

The parchment coffee beans M.C. (w.b.) are observed to have a linear behavior of a descending nature during a typical dehydration process. The authors believe this behavior is inherent of the coffee dehydration process within the HARC²S. As previously mentioned, the coffee beans temperature model is coupled to the M.C. (w.b.) prediction model. Please refer to Figure 4. The proposed M.C. (w.b.) model predicts well the behavior of the parchment coffee beans during dehydration as compared to the measured data. In this case the RMSD = 0.16907. Interestingly, the linear behavior of the M.C. (w.b.) during dehydration of the coffee beans has been observed when coffee beans are being dried using a solar rotating drum known as "bombo" [15], and not in a mechanical rotating drum type dryer known as "bateas". These bateas are the dryers of choice for the coffee processors in Puerto Rico. In open mechanical rotating drum types of dryers, the M.C. (w.b.) behavior is of a Fickian-type nature. It appears that the dehydration environment being created by the HARC²S constant adiabatic heat proves an environment that favors a non-Fickiantype of behavior. This particular feature of the HARC²S can be a favorable attribute of this equipment, since the coffee processors of Puerto Rico prefer the bombo dried parchment coffee due to its superior coffee flavor quality. However, drying parchment coffee using a non-solar energy bombo consumes large amount of energy, forcing the coffee processors of Puerto Rico to resort to other drying alternatives, i.e., open mechanical rotating drum. Therefore, an added benefit of using a HARC²S is that it provides a bombo-type quality coffee dehydration dynamics with substantial energy savings, as well as, achieving an environment that favors minimal fungal and bacteria exposure. The drying environment created by the HARC²S provides favorable conditions for the processing of safe quality coffee. Also, the parchment coffee beans M.C. (w.b.) values were plotted for the experimental data and model predictions vs. the measured leaving hot moist air relative humidity. Please refer to Figure 5. It can be observed from the Figure 5 that both the model predictions and experimentally measured M.C. (w.b.) are in good agreements. This plot illustrates the relationship between the equilibrium relative humidity surrounding the parchment coffee beans and its M.C. (w.b.).

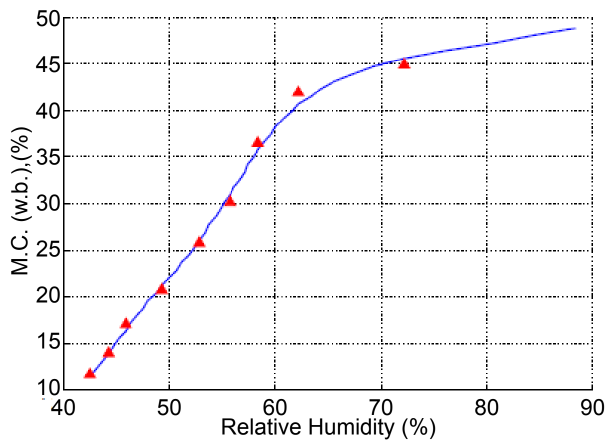

Figure 5: Depiction of parchment coffee beans MC (w.b.) vs leaving hot moist air relative humidity. The red triangles represent the measured data, the blue line represent the prediction model.

Conclusion

The concept of a HARC²S environment for parchment coffee beans dehydration have proven, based on experimental results, to have the potential to be an effective dehydration process to reduce energy consumption at coffee processing facilities, especially for the tropical climate of Puerto Rico [3]. Parametric thermodynamic models that predict parchment coffee beans temperature and M.C. (w.b.) were developed to assist the coffee processers to know the state of the coffee at all times during a drying process in the HARC²S. The thermodynamic models use hot moist air entering and leaving the coffee beans during a typical dehydration cycle in the HARC²S to determine temperature and M.C. (w.b.). The collected experimental data of parchment coffee beans temperature and M.C. (w.b.) were in excellent agreement with the models predictions. The RMSD of the temperature and M.C. (w.b.) was 0.50813 and 0.16907, respectively. Furthermore, the values of the thermodynamic models errors as compared to experimental data were within ± 1.8803% error for the temperature and ± 1.8599% error for the M.C. (w.b.).

The developed thermodynamic models are expected to be of benefit to the coffee processors when using the HARC²S for parchment coffee beans dehydration. These models will allow the processors to know the parchment coffee temperature and most importantly, its M.C. (w.b.) during the entire dehydration process without the need of opening the HARC²S to obtain samples. The benefits of not opening the HARC²S are key in maintaining: (1) dehydration environmental conditions integrity, (2) energy conservation, (3) minimize possible food contamination, and (4) maintain food security and quality.

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