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MODIFIED COFFEE DRYING SYSTEM

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ABSTRACT

The Bakker Arkema model for grain drying in deep bed was modified to simulate the process of coffee drying in deep beds using the heat and mass transfer model for thin layers proposed by Sokhansanj and Bruce (1987) and adapted for parchment coffee by Abud (1998).

A prototype of the drying bin was built and tested in the Agricultural Experimental Station in Adjuntas, Puerto Rico. This unit was used for validation of the mathematical model. The model predicts with a maximum deviation of 3% (wb) the moisture level of the bean throughout the drying process. The airflow direction was reversed in the prototype every six-hour intervals and air temperature was set at 55°C. Twenty-seven hours was needed to reach a moisture level of 11 w.b in the prototype using a flow rate of 50 cfm per square feet. A Comparison between experimental and theoretical values show a maximum deviation of 3% w.b.

Key Words: Coffee, Drying, Deep Bed, Reversal, Modeling, Simulation.

INTRODUCTION

Coffee grows in the tropics, countries in Central and South America, Africa and Asia possess high air humidity and an mean annual temperature of 20°C and above. Worldwide Coffee is considered the second most important merchandise.

Farmers take very good care of coffee trees to ensure high yields, which other wise can upset the cash flow of the farm and the availability of hand pickers during the harvest season. Hand pickers will rather work for yield farms where they can earn more money for their daily work. Coffee cherries are pulped and wash clean for the mucilaginous substance that surrounds the bean. This cleaning is done either by fermenting the sugars in the mucilage and then washing clean or by jetting water directly to the bean for physical removal of this sticky substance. Beans in the coffee cherry are wet, about 50-54% wet basis (wb) and after pulping and washing the bean gains moisture reaching 54 to 58%. Drying is therefore the next process, that under weather permitting conditions, small farmers do under the sun for several days. But in large commercial production scenarios, sun drying is not enough and artificial drying equipment has to be used. To maintain the same quality of sun dried coffee, the air temperature has to be kept at 55°C (references). Many of the substances that gives products such as coffee their typical flavor and aroma are volatile organic compounds, and would be lost in a normal drying process because they would evaporate together with water.

Farmers in Puerto Rico's coffee growing areas have used simple deep layer dryers equipped with diesel burners and electric fans. Wet parchment coffee is placed on a perforated plenum chamber where a heated air current removes water as it travels upward. A stirring mechanism stirs the coffee beans that are most adjacent to the perforated plenum chamber, but in the process this layer is overdried and most times the bean is physically damaged. In this paper, we present a mathematical formulation of the thermal processes in the deep layer coffee dryer. The system was modified to allow reversal air flow as the drying process takes place generating two drying fronts for improved quality of the end product. A prototype of the proposed alterations was built and evaluated using air flow reversal. To model the process we used the Bakker-Arkema model formulation with heat and mass transfer equations adapted from the thin layer grain drying theory.

LITERATURE REVIEW

Reversal Airflow Method and Drying Simulation.

Airflow reversal in coffee drying consists of alternating the direction of airflow though a steady layer of wet parchment coffee. In the process, coffee beans shrink and the porosity of the bed changes all throughout the process. The depth of the bed is also reduced from approximately 24-in to 18-in or less.

Air flow reversal in coffee drying has been investigated by several authors (Oliveros, 1984; Oliveros and Pinheiro, 1985; CENICAFE 1991; Alzate, 1992; Berbert et al. 1994 and 1995). Their results show better homogeneity of the dry product and a reduced moisture gradient is observed with airflow reversal. Sabbah et al. (1977 and 1979) and Dávila et al. (1983) concluded the same after drying soybean seed and rough rice, respectively.

Sabbah et al. (1979) simulated the process of deep bed drying using airflow reversal. They used a modified version of the model developed by Bakker-Arkema et al. (1974) to investigate the effect of drying conditions on the energy requirements of soybean seeds. The mean error (simulated versus observed) moisture content was 0.028 decimal with standard deviation of 0.014 decimal (dry basis).

Davila et al.1983, also adapted the Bakker-Arkema model to simulate drying rough rice. The differences between experimental and predicted values of moisture content were found to be less than 1% on the average.

Oliveros and Pinheiro (1985) applied and validate the Thompson et al. (1968) model for parchment coffee with airflow reversal in deep beds. They compared simulated results using experimental data by Correa (1982); concluding that the simulated results over-predicted the experimental values. Berbert et al. (1995) also adapted this model for coffee obtaining regression coefficient of 0.95 and the mean standard error between moisture content was 0.020 decimal d.b.

SIMULATION MODEL

Deep bed Model:

The simulation model developed in this research is basically a modified version of the Michigan State model for deep bed cited by Brooker et al. (1992). The model is based on simultaneous heat and mass transfer applied on a differential volume located at an arbitrary location in the stationary bed.

The model formulation is describe with the following equations:

for enthalpy of the air: (1)

$$\frac{\partial T}{\partial X}=\left(\frac{-h_T\ A_G}{G_a\ C_a+G_a\ C_v\ W}\right)(T-\theta)$$

for enthalpy of the grain: (2)

$$\frac{\partial \theta}{\partial t}=\left(\frac{-h_T\ A_G}{\rho_p\ C_G+\rho_p\ C_a\ M}\right)(T-\theta)+\left(\frac{h_{LG}+C_v\ (T-\theta)}{\rho_P\ C_G+\rho_p\ C_a\ M}\right)\left(G_a\ \frac{\partial W}{\partial X}\right)$$

for humidity of the air: (3)

$$\frac{\partial W}{\partial X}=-\left(\frac{\rho_P}{G_a}\right)\frac{\partial M}{\partial T}$$

The equation (4) is given by thin layer equation using either the theoretical formulation proposed by Sokhansanj and Bruce (1987), or the empirical relationship of Roa and Macedo (1976):

Thin layer equation

a) Theoretical equation:

The thin layer formulation is the basis for the deep bed model. In this research we used the model proposed by Sokhansanj and Bruce (1987) and adapted for coffee drying by Abud (1998). The thin layer formulation is:

for temperature of grain: (4) $\rho_k \, C_G \frac{\partial \theta}{\partial t} = div\left(k_G \, grad\theta\right)$

for moisture of grain: (5) $\frac{\partial M}{\partial t} = div\left(D_G \, grad \, M\right)$

Boundary conditions for equations 4 and 5 are: when ($r=R_E$), then:

for temperature of the grain:(6) $-k\frac{\partial \theta}{\partial r} = h_T\left(\theta - T\right) - \rho\left[h_{LG} + c_v\left(T - \theta\right)\right]h_m\left(M - M_E\right)$

for the moisture content of the grain: (7) $-D\frac{\partial M}{\partial r} = h_m\left(M - M_{EQ}\right)$

b) Empirical equation

We also considered the empirical equations developed by Roa and Macedo (1976) for thin layer drying. The equation relates moisture content to air vapor pressure using the following expression: (8)

$$\frac{\partial M}{\partial t} = -m\,q\left(M - M_{EQ}\right)\left(P_{vs} - (1 - HR)\right)^{n} t^{q-1}$$

where the values for the constants m, q, n depend on the air temperature and are given by Ospina and López (1990) for parchment coffee.

An analytical solution of equations (1) to (8) was developed using a combination of explicit and implicit differential scheme. The resulting expansion was programmed along with the mathematical expressions that account for the physical-thermal properties of wet parchment coffee.

PROCEDURES

The prototype used for validation of the model is circular dryer with 1.22 m circumference (Figure 1). Air ducts are 10 in diameter with damper gates to control flow direction. Trials were conducted with Coffee Arabica L., variety Caturra. Approximately 272.75 kg of fresh wet parchment coffee was used in each trial. After loading, the prototype was instrumented with T-type thermocouples, pitot tubes, differential manometers and hygrometers and connected to a data acquisition system supplied by Campbell Scientific.

Interstitial air temperature was recorded using variable length thermocouples arrayed on a 120° on the circumference. These temperatures were recorded in four layers separated 11 cm from the perforated plenum. The temperature and relative humidity of the inlet hot air was measured in the discharge duct of the blower.

The hot air temperature was controlled with thermostats. Coffee samples were taken before inverting the airflow using a grain sampler to determine moisture content and grain temperature. Coffee samples were labeled, stored and refrigerated at 5°C for further processing at the laboratory. Moisture content was determined following standard specification by ASAE (1996). Every sampling time produced four samples, one for each position in the coffee layer. Overall moisture content was estimated by average of the samples and the resulting value was used for validation of the model outcomes. The airflow for each test was obtained applying the continuity equation in the outlet duct where the air velocity was measured with digital anemometer. Goodness of fit between the simulated results and observed data was calculated by the standard deviation and the coefficient of determination.

RESULTS

Table 1 shows the drying conditions under airflow reversal and the final moisture content for the three experiments performed in Adjuntas, Puerto Rico. Airflow was regulated at 15.24 **m^3/m^2*min** comparable to other authors that use 10 **m^3/m^2-min** (Cenicafé) for deep bed equal or greater than 0.40 m.

Table 1. Operating conditions for coffee drying with airflow reversal.

Test Number	Drying Time (h)	Reversal Time (h)	Air Temperature (C)	Unit Flow (m^3/m^2*min)	AirFlow (m^3/h)	Final moisture %, w.b.
1	24,0	3,0	54,69	15,24	1067,5	12,58
2	24,0	6,0	54,78	10,00	700,47	14,95
3	24,0	6,0	54,63	15,24	1067,5	12,59

The end moisture content of 11% was not reached because the drying time was set at 24 hours and, in the three trials, this time was not enough to reach the target moisture content. The ANOVA did not find statistical significant differences of the moisture content when using the air temperature as the independent variable. Also for the same reversal time interval, an increase of airflow let reduce the mean moisture content across of the coffee bed. Increasing the airflow by 52.4% can further reduce the moisture content by 18%. Increase the air temperature above 55°C is not recommendable because detrimental results in terms of coffee quality (aroma and flavor). The value of the inlet air temperature for each test is the average given throughout the process.

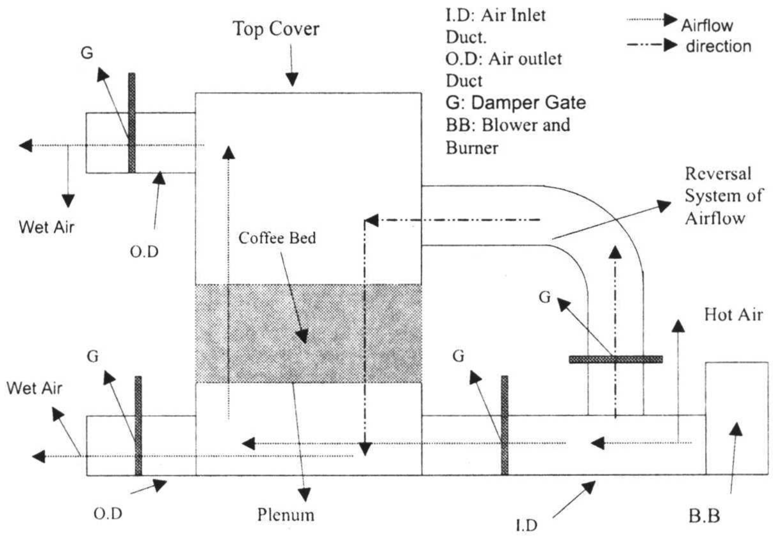

Figure 1. Deep Bed Dryer for coffee drying with airflow Reversal.

Figure 2, 3 and 4 shows the mean grain moisture content predicted by the two modeling approaches described before using the thin layer formulation of Roa and Macedo (1976), and the theoretical formulation of Sokhansanj and Bruce (1987).

The empirical model proposed by Roa and Macedo (1976) over predicted grain moisture in the early 18-hours of the test, the difference between observed and simulated is reduced in the late stages of the drying process. The theoretical approach based on the formulation by Sokhansanj and Bruce (1987); here the model tends to match the observed moisture content at the beginning of the test and slightly over predicts moisture content at the end of the test. Abud (1988) observed the same behavior working in thin layer with parchment coffee. This suggests that the Bakker-Arkema formulation can be used to model deep drying process using the thin layer theory described by Sokhansang and Bruce (1987).

Further analysis of the data shows that the standard deviation of the model with the empirical formulation was 6.89% (wb) moisture points above observed value, while that for the theoretical approach was only 2.82% (wb), showing a better fit with regard to the experimental data for all trials. The same behavior was observed throughout the drying test. The least square regression analysis of experimental and simulated moisture contents (theoretical formulation) reported coefficients of determinations of 0.94 to 0.96, respectively. However the deep bed model with empirical formulation for thin layer reached coefficients of determination from 0.89-0.92. The error in the empirical modeling approach is possibly due to the selection of values for the constant parameters in the mathematical expression relating vapor pressure deficit and the drying time. Moreover, the values used in this experiment were developed for parchment coffee grown elsewhere and not the one used in the trials.

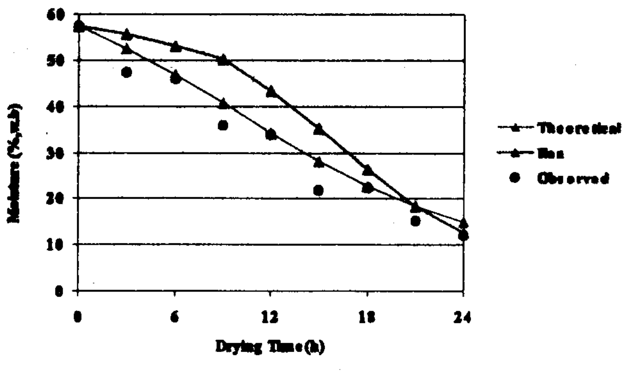

Figure 2: Observed versus simulated grain moisture content for test #1.

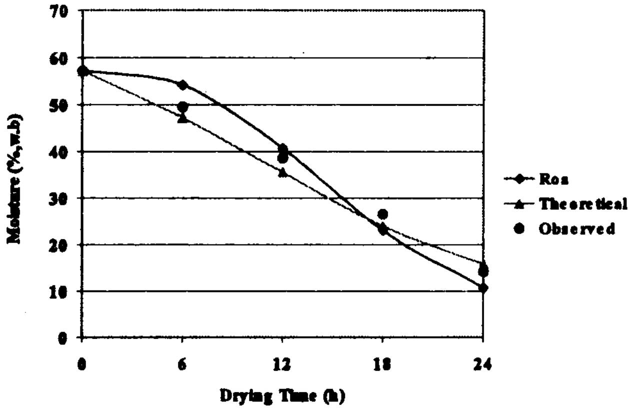

Figure 3: Observed versus simulated grain moisture contents for test #2.

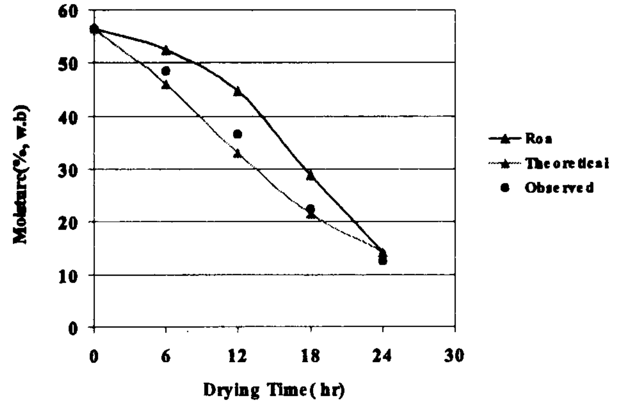

Figure 4: Observed versus simulated grain moisture content for test #3.

Another important observation from the experiments reported here is the high sensitivity of the mass transfer coefficient used in the theoretical modeling approach which is seen in Figure 5. A slight increment in the mass transfer coefficient tends to increase the rate of mass transport and therefore predicting lower moisture contents for the same drying time. This mass transfer coefficient, although a small number, has a profound effect on the model's outcomes. The optimum value of this mass transfer coefficient was $0.45 * 10^{-7}$ m/s for the temperature range and the air flow values used in this investigation. This value is within the range of acceptable values found by Abud (1998) for coffee drying simulations in thin layers. This value of h_m is approximately 4 times higher than the corresponding value found by Sokhansanj and Bruce (1989) for oatmeal grains.

Insterstitial air temperature

Figures 6 and 7 show simulated and observed interstitial air tempertaures for trials 2 and 3. The simulation model using the theoretical formulation of Sokhansanj and Bruce (1989) tends to over predict air temperature throughout the drying process. However, the empirical formulation of Roa and Macedo (1976) does a better job predicting interstitial air temperature in the drying bed. The overall standard deviation of using the empirical approach was 5.65 °C, while the theoretical approach was 7.92 °C. The empirical model better predicts temperature while the theoretical model does a better job predicting grain moisture content.

CONCLUSIONS

The following conclusion can be obtained from this study:

For modeling the drying process in coffee with airflow reversal, the version modified of the model developed by Bakker-Arkema et al. (1974) for deep bed

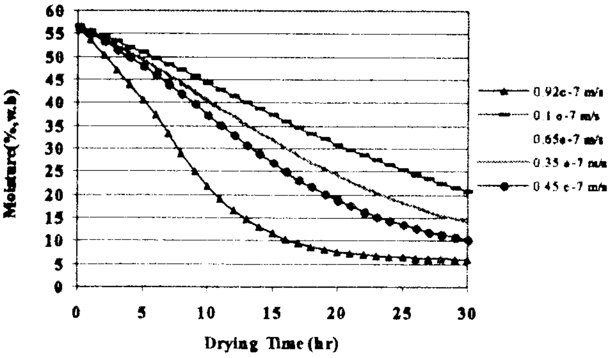

Figure 5: Sensitivity of the mass transfer coefficient h_m in coffee drying simulations in deep bed.

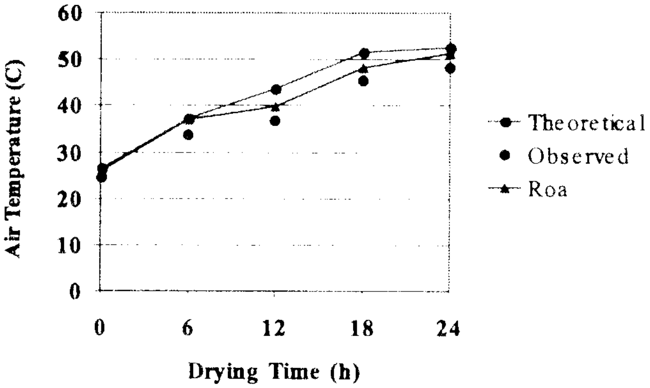

Figure 6: Observed versus simulated interstitial air temperatures for test 3.

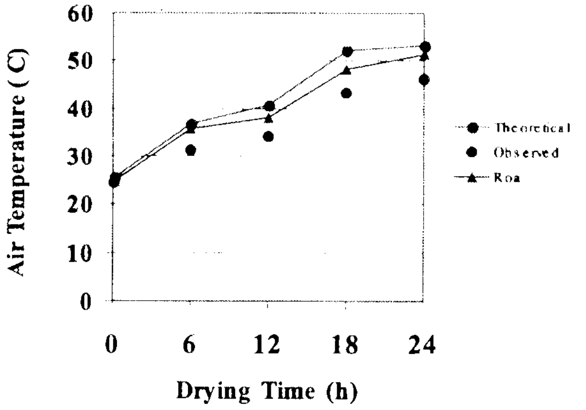

Figure 7: Observed versus simulated interstitial air temperatures for test 2.

dryer is successfully predict the variation of the moisture content.

The deep bed model using the thin layer model developed by Sokhansanj and Bruce (1987) and adapted for parchment coffee drying by Abud (1998) provide good prediction of observed mean moisture content profiles.

Using the deep bed models the choice of the value of the mass transfer coefficient can significantly affect the results derived of the simulations.

The model in deep bed proposed by Bakker Arkema et al (1974) over predicts the mean air temperature inside coffee grain bed. Predictions of temperatures profile were no good, particularly in the stages intermediates of drying process.

The choice of the thin layer model significantly affects the results given by the simulation model in deep bed.

APPENDIX A. PHYSICAL, THERMAL AND HYGROSCOPIC PROPERTIES OF THE WET PARCHMENT COFFEE USED IN THIS SIMULATION STUDY.

Physical Properties:

a. Equivalent Radii

$R_E=3.94 * 10^{-3}$ m (Ciro 2000)

b. Specific Area

$A_G= 763.01$ m²/m³ (Ciro 2000)

c. Kernel density

$\_{k} = 703.48+230.3\, M_{dec\ w.b}$ (Abud,1998)

d. Bulk Density

$\_{p}= 282.4+5.993\, M_{\%\ w.b}$ (Ciro, 2000)

Thermal Properties

Bulk Specific Heat

$C_G= 1.6552+0.05835\, M_{\%\ w.b.}$ (Ciro,2000)

Bulk ThermalConductivity

$k_G= 0.00830+0.02363\, M_{dec\ w.b}$ (Abud,1998)

Hygroscopic Properties

Latent Heat of Evaporation (Trejos,1986)

Equilibrium Moisture Content (Trejos,1986)

where

and

$D_G= 4.1582*10^{-8}EXP((0.1346\_C +2.2055)M_{decd.b}-1148\ (\_C+273.16)^{-1})$

(Montoya,1989)

APPENDIX B. LIST OF SYMBOLS

- AG: Specific area of the grain, m2/m3
- c: Diffusion Coefficient of grain
- Ca: Specific heat of dry air, kJ/ kg K
- CG: Specific heat of parchment coffee grain, kJ/ kg K
- Cv: Specifc heat of moist air, kJ/ kg K
- Cw: Specifc heat of water, kJ/ kg K
- DG: Water diffusion coefficient of grain, m2/h
- Ga: Air flow rate, kg/h*m2
- hLG: Latent heat of evaporation, kJ/kg
- hm: Mass transfer coefficient, m/s
- HR: Relative humidity, decimal
- ht: Heat transfer coefficient, W/m2 K
- kG: Bulk thermal conductivity, W/m K
- M: Moisture content, decimal dry basis.
- ME: Equilibrium moisture content, dry basis (decimal)
- Pvs: Saturated vapor pressure, Kpa
- r: Radial coordinate, m
- RE: Equivalent radii of grain, m
- T: Air temperature, K.
- TC: Air Temperature of Drying, 0C.
- t: Drying time, h
- W: Humidity ratio, kg water/kg dry air
- X: Bed depth, m
- q: Grain temperature, K
- qC: Grain Temperature, 0C.
- r: Water density, kg/m3
- rp: Bulk density, kg/m3
- rk: kernel density, kg/m3

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