Mathematical Modeling of a Tray Dryer for the Drying of Potato Chips Using Hot Air Medium

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ABSTRACT

The mathematical model of a batch tray dryer for the drying of potato chips using hot air medium has been developed. During this processes, the conservation principle was applied to the fundamental quantities of mass of moisture in Potato, mass of moisture (humidity) in air and energy of potato and energy in air. The model equations were solved using the fourth order Runge-kutta algorithm and implemented in a visual basic program. The results from the program shows that the air temperature initially drops as it enters into the dryer due to the high moisture content in the potato but later starts to increase and stabilized as the time in the dryer progresses and also the temperature of the potato increases as the time in the dryer increases. From the results it was also found out that as the time spent in the dryer increases, the moisture content in the food decreases while the air humidity increases. These predictions are in agreement with cited available literature. Functional parameters in the dryer such as quantity of heat supplied and air flow rate were also simulated for process control and optimization.

Keywords : Mathematical Modeling, Batch tray dryer, Material, Energy balance.

1 INTRODUCTION

THIS Human have preserved foods by drying since ancient times. Drying is one of the oldest methods of preserving foods. Primitive societies practiced the drying of meat and fish in the sun long before recorded history. Today, the drying of foods is still important as a method of preserving foods. Dried foods can be stored without deterioration occurring [1]. Drying of foods is carried out for the following reasons.

1. Micro-organisms which cause food spoilage and decay are unable to grow and multiply in the absence of sufficient water and many enzymes which promote undesired changes in the chemical composition of the food cannot function without water.
2. Dried foods are easy to transport and store because they occupy only about one – tenth the volume of the fresh food.
3. Dried foods are most suitable for handling.

[2], [3], [4] also outlined that drying of foods involve the removal of water from the food stuff, in most cases drying is accomplished by vaporizing the water that is contained in the food and to do this the latent heat of vaporization must be supplied, there are thus two important process controlling factors that enters into the unit operation of drying, they include;

1. Transfer of heat to provide the necessary latent heat of vaporization.
2. Movement of water or movements of water vapor through the food material and then away from it to effect separation of water from the food material.

2. MODEL DEVELOPMENT

2.1 Tray dryer modeling

Consider the batch tray dryer system used in drying of potato chips in the figure below.

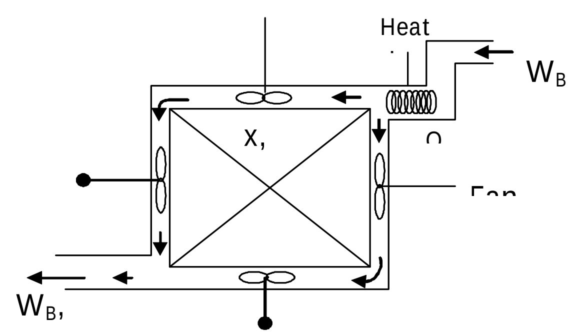

Fig.1. Typical Batch Tray Dryer

Where

W_B	=	Mass flow rate of air in kg/s
y_o	=	Absolute humidity at inlet in kg/kg dry basis
y	=	Absolute humidity at outlet in kg/kg dry basis
x	=	moisture content in the potato in kg/kg dry basis
T_m	=	temperature of potato (solid) in Kelvin
T_{go}	=	temperature of humid gas at inlet in Kelvin
T_g	=	temperature of humid gas at outlet in Kelvin
Q	=	power rating of the heating coil in kW

The assumptions adopted in modeling the small scale batch tray dryer are summarized as follows.

1. The tray dryer under goes a batch process.
2. The material – to – material contact is negligible.
3. The shrinkage in the potato material is negligible
4. The moisture content in the potato material is uniform.
5. The walls of the dryer are highly insulated, hence adiabatic condition is assumed.
6. The temperature gradient within the potato chips is negligible.
7. The air within the dryer is perfectly mixed, hence the stream of air leaving the dryer has the same parameters as the air inside the dryer
8. Accumulation is the gas phase is assumed to be negligible because it is assumed that the gas phase instantly follows changes of other parameters because the changes of gas parameters are much faster than changes in the solid.

Fig 1 shows the state variables of the batch tray dryer and they include moisture content x, Air humidity y, temperature of solid T_m and temperature of humid air T_g.
Since the drying medium is hot air, the fundamental quantities whose values provides information about the batch drying are

1. Mass of moisture in the potato (solid phase)
2. Mass of moisture (humidity) in air (gas phase)
3. Energy of the potato
4. Energy of air.

Mass balance on potato (solid phase)

$$\frac{dx}{dt} = -W_D \frac{A}{M_S} \qquad (1)$$

Mass balance on air (gas phase)

$$W_B Y_0 - W_B Y + W_D A = 0 \qquad (2)$$

Energy balance on potato (solid phase)

$$\frac{dT_m}{dt} = \frac{A\left[\alpha\left(T_g - T_m\right) + W_D\left[\left(C_{A1} - C_A\right)T_m - \Delta h_{vo}\right]\right]}{M_S\left(C_S + C_{A1} X\right)} \qquad (3)$$

Energy balance on air (gas phase)

$$W_B\left[\left(C_B + C_A Y_o\right)T_{go} - \left(C_B + C_A Y\right)T_g - C_A T_g\left(Y - Y_o\right)\right] - A\begin{bmatrix}\alpha\left(T_g - T_m\right) - \\ W_D C_A\left(T_g - T_m\right)\end{bmatrix} + Q = 0 \qquad (4)$$

OPERATING PARAMETERS

PARAMETER	UNITS	VALUE
Moisture content in potato before drying, Xo	kg/kg	0.75
Mass of potato, M_S	Kg	50
Interfacial area of phase contact, A	m^2	1.3667×10^{-3}
Mass flow rate air, W_B	Kg/s	0.1
Absolute air humidity at inlet, Y_o	Kg/kg	0.002
Convective heat transfer coefficient, $\propto$	Kw/m^3 K	1.57×10^{-4}
Specific heat capacity of the liquid phase, C_{A1}	KJ/Kg K	4.2
Specific heat capacity of the vapor phase, C_A	KJ/Kg K	1.876
Specific heat capacity of potato, C_s	KJ/Kg K	3.515
Specific heat capacity of dry air, C_B	KJ/Kg K	1.007
Temperature of humid air at inlet, T_{go}	K	293
Quantity of heat supplied per unit time, Q	KW	20

The rate of drying used in this work is given by McCabe et al[13] and is given as

$$W_D = M_S\left(dx / Adt\right) \qquad (5)$$

3 RESULTS AND DISCUSSION

3.1 Variation of Moisture Content and Air Humidity with Dimensionless Time

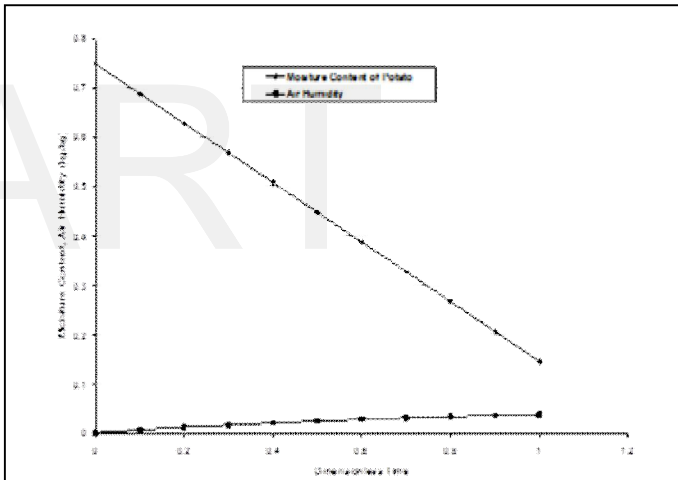

Fig. 2. Variation of Moisture Content and Air Humidity with Dimensionless Time

In general drying processes, the moisture content in the material been dried reduces as the drying time of the potato material in the dryer and the air used to effect the drying gets more humid as resident time in the dryer increases [5], [6], [7], [9], [10]. Fig 2 shows how moisture content and air humidity varies with time. The chart of Fig 2 shows the dependence of the moisture content and air humidity on the dimensionless time. As the residence time in the dryer increases the moisture content in the food decreases in a linear proportion of about 80% of the total moisture in the potato. This is a function of the amount of heat transferred to the potato. This observation qualitatively agrees with the work [5], [6], [7], [9], [10]. Also, air humidity increases linearly. This is evident because as the moisture content in the food is removed, the air in the dryer receives the moisture and gets more humid, which is also a

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function of the amount of heat supplied to the air and the air-flow rate.

3.2 Variation of Outlet Air Temperature and Potato Temperature with Dimensionless Time

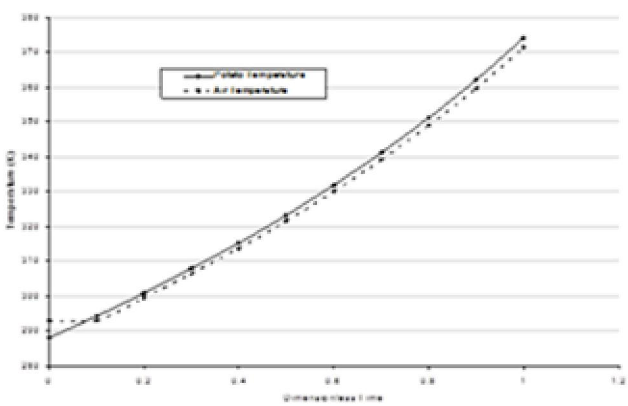

Fig. 3. Variation of Outlet Air Temperature and Potato Temperature with Dimensionless Time

In general, as reported in the study of [5], [6] and [8], the temperature of the hot air exiting or leaving the exhaust of a dryer is of higher temperature than that of the inlet air. Fig. 3 shows how the outlet air temperature and the potato temperature varies with dimensionless time. From Fig. 3 it is clearly seen that the variation of the outlet air temperature with the dimensionless time agrees with what was reported in [5], [6], [8] except for a slight variation from what is found in [5], [6] and [8]. It can be seen that there is an initial drop in the outlet air temperature. This is because at the start of the drying process, the surface of the potato contains free moisture which initially drops the temperature of the inlet air, so as the residence time of the potato chips in the dryer increases heat energy that is used to heat up the moisture in the potato to its boiling point. As the moisture in the potato starts to evaporate, then temperature of the outlet air starts increasing as the potato evaporates the moisture contained in it. The air temperature also increases excessively due to the constant power been supplied to the internal heater [6]. Also, as the residence time increases and heat energy is supplied to the potato, moisture content is continually removed from it. The potato chips gradually conduct heat as it gets dried its temperature increases.

3.3 Variation of Quantity of Heat Supplied with Air Temperature

Fig 4 below shows how varying the quantity of heat supplied affects the air temperature.

In the model of equation 3.0 the value of the power rating of the heating coil used is 20KW, but varying it in steps of 20KW shows that the air temperature increases accordingly as shown in Fig. 4 so an increase in the quantity of heat supplied, increases the air temperature.

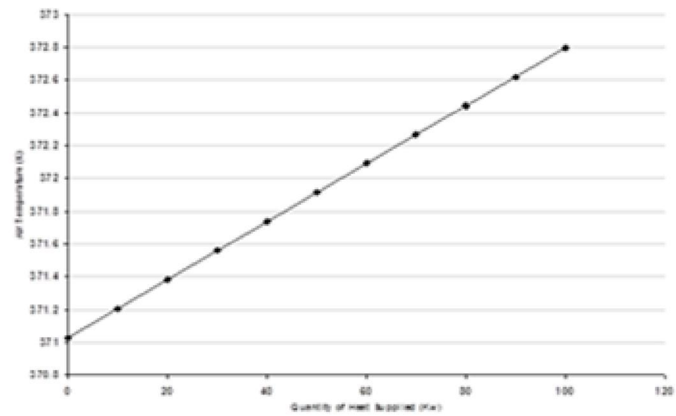

Fig. 4. Variation of quantity of heat supplied with air temperature

3.4 Variation of air flow rate with air humidity

Fig 5 below shows how varying air flow rate affects air humidity. The plot clearly shows that as the air flow rate increases, the air humidity also increases, this is because the faster the flow of the inlet air, the more it collects moisture from the potato making it more humid.

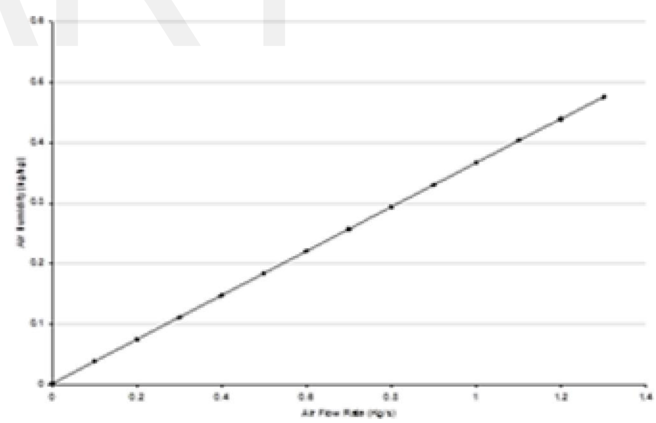

Fig. 5. Variation of Air Flow Rate with Air Humidity

3.5 Variation of Air Flow Rate with Air Temperature

Fig 6 below shows how air flow rate varies with the air temperature. From the plot, it is clearly seen that increase in the air flow rate reduces the air temperature. As air flow rate increases the moisture content in the air also increases. The higher the humidity of the air, the lesser its temperature, so increase in the air flow rate cools down the temperature of the air.

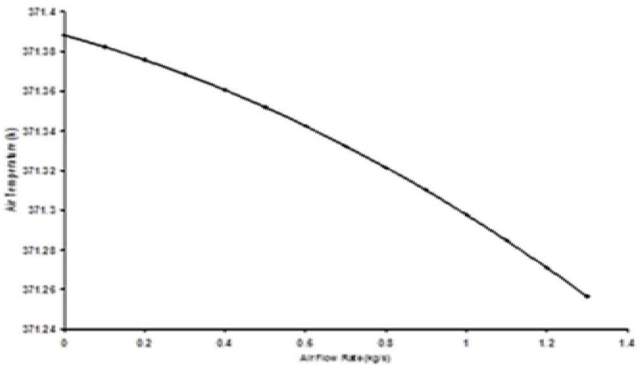

Fig. 6. Variation of Air Flow Rate with Air Temperature

4 CONCLUSION

A model to predict the drying of potato chips in a batch tray dryer using hot-air medium was developed. The conservation principle was applied to the fundamental quantities such as mass of moisture in the potato, mass of moisture (humidity) in air, energy of potato and energy of air to obtain the state equations that describe the dynamic behavior of the batch tray dryer using hot-air medium. A visual basic program was also developed to solve the model equations in order to determine the various output variables (state variables) using appropriate initial conditions. All the parameters and physical properties required to solve the models were obtained from literatures. Results from the model shows that the moisture content in the potato chips reduces while the air humidity increases as the time in the dryer progresses, also the air temperature and potato temperature increases as the time increases. The simulation results agree closely to existing literature.

NOMENCLETURE

Symbols	Meaning	Units
A	Interfacial area of phase contact	m^2
C_A	Specific heat capacity of the vapor phase	KJ/KgK
C_{A1}	Specific heat capacity of the liquid phase	$KJ/Kg\,K$
C_B	Specific heat capacity of air	$KJ/Kg\,K$
C_S	Specific heat capacity of potato	$KJ/Kg\,K$
h_A	Specific enthalpy of steam emanating from the solid	KJ/Kg
Δh_{vo}	Latent heat of vaporization	KJ/Kg
Ig	Specific enthalpy of humid gas	KJ/Kg
Im	Specific enthalpy of wet potato	KJ/Kg
M_B	Mass of air	Kg
M_s	Mass of potato	Kg
q_h	Convectional heat flux	Kw/m^2
Q	Heat supplied by heat coil	KW
Tg	Temperature of air	Kelvins
Tm	Temperature of potato	Kelvins
t	Instantaneous time	S
W_B	Mass flow rate of air	Kg/s
W_D	Rate of Moisture removal per unit surface area	$Kg/m^2\,S$
Ws	Mass flow rate of potato	Kg/s
X	Moisture content in potato	Kg/Kg
Y	Absolute humidity in air	Kg/Kg

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