Dynamic Models for Predicting the Moisture Content of Food Chips During Packaged in Polypropylene Plastic Film

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ABSTRACT

The main problem in storage of dry food chips is water absorption. Dried foods tend to absorb moisture from free air. Flexible packaging can reduce the water absorption on foods and as the result it may prolong the shelf lives of the products. However, most flexible package materials are not fully impermeable. The moisture of the products in the package slowly increases until it reaches the moisture equilibrium. Accordingly, the objectives of this study were to develop mathematical models for predicting and to simulate the estimation of the moisture content of food chips during stored on permeable packages. The mathematical models developed were based on water vapor migration trough a permeable film, rate of moisture sorption by foods, equilibrium moisture content and water mass balance. Samples for the experiment were food chips made from gnetum seeds of local production. The gnetum (emping) chips were placed on stainless steel cups. The mouth of the cups were covered using polypropylene plastics as the package models. The cups were stored in glass bottles. The relative humidities of the storage atmosphere in the bottles were adjusted using saturated solution of salts such that the humidity ranges were between 10% to 95%. The changes of moisture content of the fried chips were observed for about twenty five (25) days until they reach their equilibrium moisture contents. The results indicate that the dynamic models can predict the moisture contents of fried chips in package quite well. The estimation of the water vapor migration trough the plastic film seems slower than the observed moisture absorption especially at low moisture contents.

INTRODUCTION

The common problem in storage of food chips is water vapor absorption. Water vapor absorption makes the product loss their crispiness and the foods considerably are not tasteful. Additionally, the increasing water contents of foods can stimulate the growth of mold and consequently shortens the storage lives of the products. As hygroscopic products, dry foods tend to absorb water vapor from free atmospheric air. Placing the product in package can reduce the water absorption. The package is intented to protect the products from moisture and oxygen at level potentially can deteriorate the products (Hayakawa et al., 1975; Gilbert, 1976; Smith et al., 1983). Several types of plastic films are available for packaging of dry foods. However, plastic film is not fully impermeable from moisture and gases. The moist of air is still capable to migrate through the film. The moisture migration occurs through the film to the available package space. Plastic sheet has certain gas permeability and its rate depends on the film thickness, the type of plastics, micro structure of plastics, and other parameters (Labuza et al., 1972; Gilbert, 1976; Hayakawa et al., 1976).

Limited publications on estimating the moisture contents of products in package are available. A lot of research have been conducted to predict the concentration of several gas and water vapor in packages. Gilbert (1976) studied the migration of the volatile gases and water vapor through food packaging. He developed model based on theory of sorption and on theory of Gibb for the mass balance between liquid phase and gas phase, and combined with permeability of gas through plastic film. Hayakawa et al., (1976) developed formulae for calculating the changes of gas contents in polymeric packages. They used a model based on analyses of mass balance and then using simulation they predicted the gas contents inside the packages. Mizrahi and Karel (1977) developed model of water vapor sorption by product in packages. They used the exponential sorption of water by agriculture commodities to develop their model. Rahardjo et al. (1997) used simplified linear model to estimate the moisture contents of dry food chips in packages made from polypropylene film. Other research reported the changes of water content of agricultural product during in packages. However, there is limited information on water content changes of dry food during in package (Brown, 1992; Smith et al., 1983).

Accordingly the objectives of this study were to develop mathematical models for predicting and to simulate the estimation of the moisture content of food chips during stored on permeable packages. Whenever acceptable ranges of the moisture contents of dry foods are available, the model can be used estimate appropriately the storage lives of the products during packaged in permeable plastic film.

MATERIALS AND METHODS

Mathematical models

The driving force of water vapor migration through a plastic membrane is mainly the difference of the partial pressure of the water vapor p_1 inside package and that of p_0 outside of package. Therefore the rate of water vapor migration analogically can be expressed using the first Fick's law as follows (Labuza et al. 1972; Brown, 1992; Rahardjo et al., 1997).

$$\frac{dm_v}{dt} = AP_m \frac{[p_o - p_i(t)]}{d} \qquad (1)$$

Correspondingly the water vapor pressure p_v, can be expressed using atmospheric relative humidity as follows:

$$p_v = p_s H \qquad (2)$$

Accordingly the rate of water vapor migration can be expressed using the difference between the humidity inside package and the humidity outside of package. Therefore equation (1) can be modified as the following equation:

$$\frac{dm_v}{dt} = AP_m P_s \frac{[H_o - H_i(t)]}{d} \qquad (3)$$

The total mass of water m_v inside the package is equal to the sum of water vapor mass m_a in the air inside the package and the mass of water m_w in the packed food as follows:

$$m_v = m_a + m_w \qquad (4)$$

The moist mass m_a in the air inside the package can be expressed as an ideal gas as follows:

$$m_a = \frac{18\,Vp_s}{RT} H_i(t) \qquad (5)$$

The water mass m_w in the food material can be related to the moisture content M and the dry weight D of food material as follows:

$$m_w = D\,M(t) \qquad (6)$$

The rate of water vapor adsorbed by the food materials and the rate of water vapor change in the atmosphere inside package is the derivative of equation (6) as follows:

$$\frac{dm_v}{dt} = \frac{18\,Vp_s}{RT} \frac{dH_i}{dt} + D\frac{dM}{dt} \qquad (7)$$

Based on the mass balance, equation (7) is equal to equation (3). Therefore the following equation expresses the rate of relative humidity change:

$$\frac{dH_i}{dt} = \frac{Ap_mRT}{18V} \frac{[H_o - H_i)}{d} - \frac{DRT}{18\,Vp_s} \frac{dM}{dt} \qquad (8)$$

The water absorption by the dry food material can be described as the drying rate of single kernel. Since the thickness the food sample is small enough, the moisture of the food can be assumed homogeneous. Based on the mass balance of the water vapor entering the food chips therefore the change of moisture mass in the chip can be described as follows:

$$\frac{dM(t)}{dt} = \frac{A\,k_c}{D} (H_i - H_s) \qquad (9)$$
$$= k\,(H_i - H_s)$$

The dry food assumably is with uniform thickness h such that the dry food weight D is proportional to the surface area A or D = p(rho)A. Therefore the value of Ak_c/D in equation (9) is equal to the constant rate of water vapor absorption k. Inserting equation (9) into equation (8) the rate of relative humidity change inside the package is as follows:

$$\frac{dH_i}{dt} = \frac{Ap_mRT}{18\,V} \frac{[H_o - H_i]}{d} - \frac{DkRT}{18\,Vp_s} [H_i - H_s] \qquad (10)$$

Moreover the food chip is very thin such that its moisture content is assumably homogeneous and equals to the moisture content M. Considering that the moisture content M is in equilibrium with the relative humidity H_s in the food surface, the relation of the equilibrium moisture content and the relative humidity can be described by the Guggeinheim Anderson de Boer (GAB) model as follows:

$$M(t) = \frac{M_o YKH_s}{(1 - KH_s) \times (1 - KH_s + YKH_s)} \qquad (11)$$

The moisture content to the humidity relationship can be simplified using the proportionality K_s as the ratio of M to H_s. or as $M(t)=K_sH_s(t)$. Accordingly the proportionality K_s will not linear to H_s. It will change as the H_s changes.

The rate of the water adsorption by the dry material can be expressed using the derivative of equation (9). The rate of the equilibrium moisture content changes dM_e/dt due to the change of relative humidity inside the package is small and therefore is ignorable. Accordingly the rate of the water vapor absorption by the food materials can be expressed as follows:

$$\frac{dH_s}{dt} = \frac{k}{K_s}[H_i - H_s] \qquad (12)$$

Solution of the integration of equation (10) will be the equation usable to estimate the relative humidity inside the package during storage duration t. However, the solution will be complex. Discretizing the storage duration t into m numbers of small interval time Δt, the relative humidity of the air inside the package can be expressed as follows:

$$H_{im} = H_{i0} + \sum_{n=1}^{m} \left(\frac{Ap_mRT}{18\,V}\,\frac{[H_o - H_{in}]}{d} - \frac{DkRT}{18\,Vp_s}[H_{in} - H_{sn}]\right) \Delta t \qquad (13)$$

Using the same way of equation (13), the integration of equation (12) is as follows:

$$H_{sm} = H_{s0} + \sum_{n=1}^{m} \frac{k}{K_s}[H_{in} - H_{sn}]\,\Delta t \qquad (14)$$

Equation (11) determines the proportionality value of K_s as M/H_s. Vice versa the food moisture is calculated from the food surface humidity by the relation of $M = K_sH_s$. Therefore based on equations (11), (13) and (14), therefore a computer program can be developed to simulate for predicting the moisture contents of dry food products during storage in packages.

Samples

Samples for the experiment were chips made from gnetum seeds (*Gnetum gnemon, emping chips*) of local production. The dried gnetum chips were fried using oil for about 15 seconds and then the oil was drained for more than two hours. The fried chips then were dried in oven at 70°C for about 24 hours until the moisture contents were less than 4% dry basis.

Humidity adjustment

Solutions of saturated salts were used to adjust the humidity of the atmosphere surrounding the package models. The salts used were LiCI, MgCI, $MgNO_3$, NaCI, KCI and KNO_3. The saturated salt solutions at room temperature (28°C) create equilibrium relative humidities at about 11.3%, 32.4%, 51.4%, 75.1%, 83.6% and 92.3% respectively (Gustafson, 1997).

Package model

The packages were cups of stainless steel with mouth opening area of about 21.6 cm^2. The cup mouth was covered by a polypropylene plastic sheet with thickness of 0.04 mm. The wall of the stainless steel cups provide imperbeable surface. Therefore the water vapor migration could be considered only through the permeable plastic film at the cup mouth. The permeability of the polypropylene film was measured based on pure water vapor migration and was found to be about $3{,}36\ 10^{-12}$ kg/s m kPa (0,0039 g cm/day m^2 mmHg). Plastic film with high permeability was chosen such that the water vapor migration is relatively fast in order to minimize the experimental duration.

Equilibrium moisture content

The equilibrium moisture contents of the samples were determined using equation of the water adsorption rate as follows:

$$\frac{dM(t)}{dt} = kM(t) - kM_e \qquad (15)$$

The constants of k and M_e can be found from the linear regression analysis based on equation (15). The equilibrium moisture contents between the available data were calculated using Lagrange Interpolating Polynomials (Chapra and Canale, 1985).

Experimental procedures

Samples were weighed and then placed in the stainless steel cups. The mouth of the cups were covered by polypropylene plastic sheet and then placed in glass bottles. The humidities in the bottles were adjusted using appropriate salt solutions. Samples were stored for 25 days. Every day or two-day the samples were weighed until they reach around their equilibrium moisture contents. The water contents of the samples were determined using oven method. The samples were dried at temperature of 105°C for 24 hours.

Data analyses and simulation

The equilibrium moisture contents of the samples were calculated using equation (15). The equilibrium moisture contents were related to the controlied humidities based on equation (11). Based on equations (13) and (14), a computer program was written using BASIC to simulate the prediction of the moisture contents of the dry chips. Table 1 shows the constants of the packages and the atmospheric conditions used for the simulation. Instead of using equation (11), the Lagrange Interpolation Method was used to calculate the equilibrium moisture contents between the available data. The moisture contents of the samples from the simulation were compared to that from observation using linear regression program (QPro, Borland).

Table 1. **Constants used for the estimation of moisture content of dry foods and air humidity in polypropylene packages.**

Description	Unit	Quantity
Permeable package surface area, A	m^2	0.00216
Net package volume, V	m3	0,0000492
Plastic thickness, d	m	0.00004
Plastic permeability, p_m	kg/s m kPa (kg/d m kPa)	3.36 10^{-12} (8.64 10^{-8})
Gas constant, R	kPa m3/kmol K	8.314
Room temperature, T	oC (K)	28 (301)
Partial pressure of saturated water vapor at room temperature, p_s	kPa	3.82
Outside package relative humidity, Ho		0.751 0.836 0.923
Dry weight of food samples, D	kg	0.003
Initial moisture content of the samples, M_0	kg water/kg dry weight	0.36

RESULTS AND DISCUSSION

During packaged as the elapsed time increases, moisture contents of the samples increase at rates t depend on the driving forces. Figure 1 shows the mo ture contents of the emping chips during kept packages with the storage atmospheric humidities 0.751, 0.836 and 0.923. Eventhough the rates of mo ture absorption are not equal depend on the storage h midities, the graphs show that the moisture contents the samples changing with same pattern. The higher humidities of the storage room will be the higher moisture reached by the samples as indicated by eq tions (13) and (14). As shown on the graphs, at ea storage humidities the moisture absorption rates incre after the moisture contents of the samples reach at ab 10% (DB). It seems that the increasing rates of the mo ture absorption accord with the curve of the moist content-relative humidity relationship.

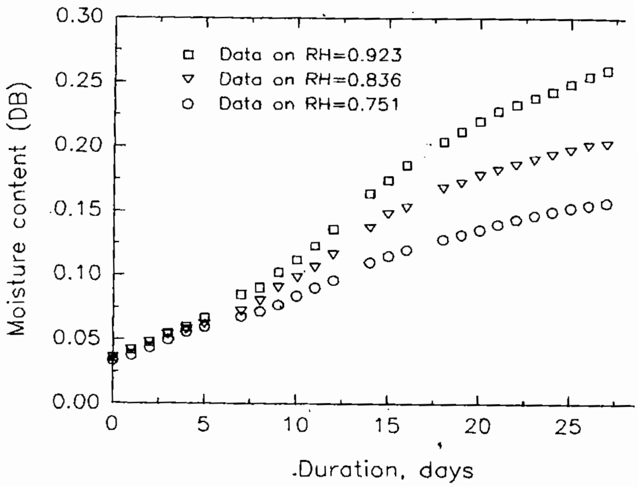

Figure 1. **The moisture contents of dry foods during in polypr pylene packages.**

As described by equation (11), the equilibrium moi ture contents of the samples increase as the humidit increases. Figure 2 shows the relation of the equilibriu moisture contents of the emping chips under sever storage humidities. The graph shows that proportiona lity K_s of the moisture content to the air humidit increases as the humidity increases. The most significant changes of the proportionality K_s is at about food moisture content of 10% (DB). The increasing proportionality means that at constant humidity migration passing the film the food moisture content changes will be faster at figher moisture content.

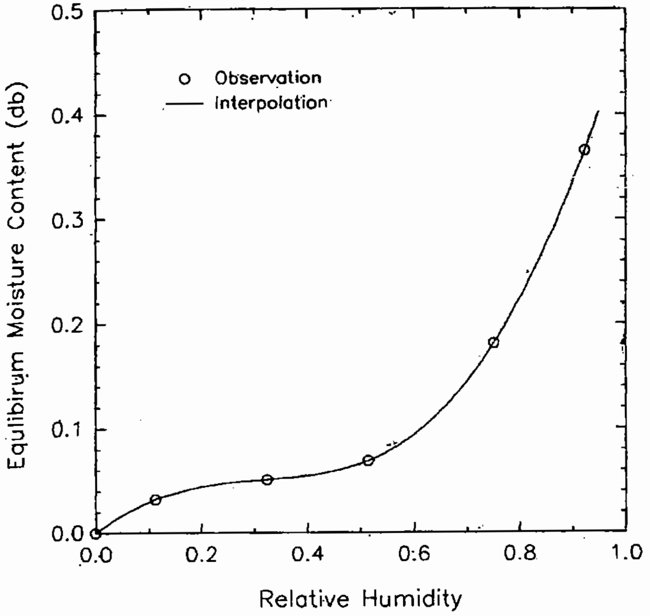

Figure 2. **The Equilibrium Moisture Content of emping (gnetum) chips under controlled relative humidities. The method used to calculate the equilibrium moisture contents between available data was the Lagrange Interpolating Polynomials.**

The constant of the moisture sorption rate k as described in equation (10) was determined using the history of the moisture contents at several levels of storage humidities. The calculated constant of the moisture sorption rate k was about 0.12 - 0.18 1/day or with average of 0.16 1/day. The computer program used the package constants shown on Table 1 and the k value at 0.16 1/day to estimate the humidity inside packages and the moisture content of the food products. Figure 3 shows the predicted moisture contents of the samples with three levels of atmospheric humidities. The graphs show that the estimated moisture contents close to that of the observation. It seems that the model can estimate the moisture contents of the products inside the package quite well. However, the estimation of the moisture content at low values is not as well as that at high moisture contents. The changes of the absorption rate of the estimation occur faster than that of the observation. Additionally the estimated moisture contents tend lower than that of observation. However, the estimation can follow the tendency of the moisture changes.

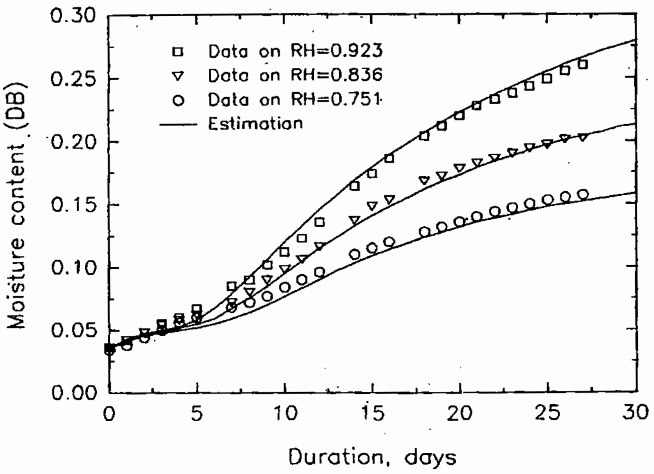

Figure 3. **Curve fitting of the observed moisture content (DB) with the moisture content estimated using the dynamic model.**

The value of the moisture absorption rate k does not significantly affect the moisture contents gained by the samples. The value of k only determines on how close the food surface humidity to the package space humidity (Figure 5). At higher value of k, the food surface humidity will be closer to the package space humidity. The ratio of the package surface A to the space package volume V is the most critical value that determines the moisture contents of foods in packages. The higher the value A/D will be the faster the moisture content increase. Food engineer must consider carefully the ratio A/V in food packaging design in order to reduce the food moisture gain rate.

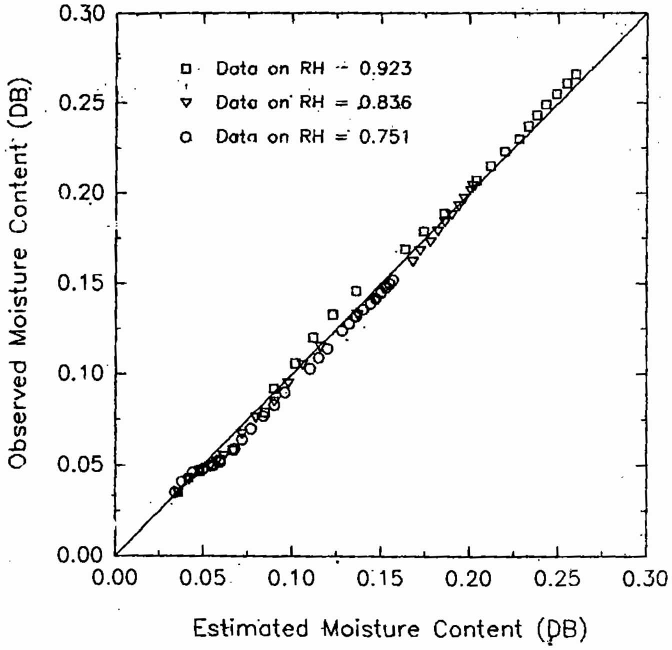

Figure 4. **The scatter plot of the observed moisture content (DB) and the calculated moisture content (DB) of the dry foods during packaged by polypropylene plastic.**

The estimation of the moisture content was based on the humidity at the food surface. Using the relation of the equilibrium moisture content with the relative humidity, the moisture contents therefore can be estimated. Furthermore the estimation of the surface humidity is related to the packages space humidity based on simplified single kernel moisture sorption. Accordingly the model can be used to calculated the humidity inside the packages. Figure 5 shows the humidities of the air inside the package and on food surface under atmospheric storage humidity of 0.923. Accordingly if the critical moisture contents of dry food are available, the storage life of foods packaged on certain permeable film can be calculated. The program can be terminated whenever the moisture contents exceed the critical values.

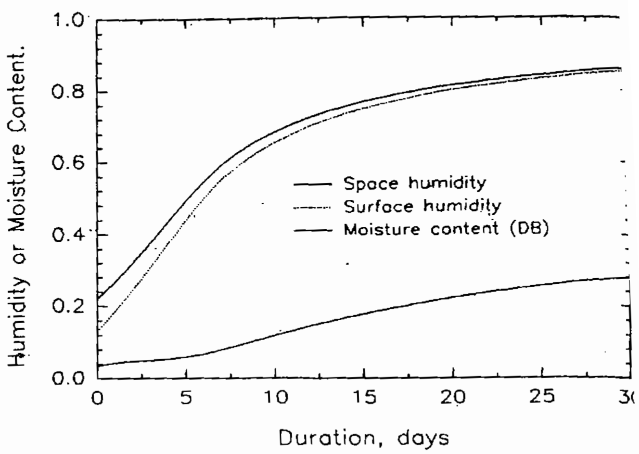

Figure 5. **The estimated package space humidity, food surfac humidity and moisture content of food chip stored a room humidity of 0.923.**

CONCLUSIONS

The dynamic models can estimate the moisture content of the dry food chips during packaged in polypropylene quite well. The estimated moisture contents tend to follow the patterns of the observed moisture contents. However, the estimated moisture contents indicate to be slower than the observed data. The slower changes might be due to the equilibrium moisture content of the samples were not exactly equal to that on the graph. Nevertheless, at higher moisture contents the dynamic models can predict them quite well. The moisture absorption rate k is not the critical value to determine the moisture contents of foods during in packages. It seems that the ratio of the surface area to the volume of the packages is the most significant parameter in designing the food packaging.

Symbols

A : package surface area, m^2
a : constant number
B : molecular weight, kg/kmol
b : constant number
c : constant number
D : weight of dry food, kg
d : plastic film thickness, m
H : relative humidity, decimal or %

h : food thickness, m
K : constant of the Guggeinheim Anderson de Boer (GAB) model
K_s : proportionality of food moisture to equilibrium humidity
k : constant of absorption rate, 1/d or 1/s
k_c : surface mass transfer coefficient based on the humidity gradient, kg/s m^2
M : moisture content, decimal or % dry basis
M_e : equilibrium moisture content, decimal or % dry basis
M_o : monolayer moisture content, decimal or % dry basis
m : mass, kg
p_v : partial pressure of water vapor, kPa
p_m : plastic film permeability, kg/s m kPa
p_s : partial pressure of saturated water vapor, kPa
R : gas constant, kPa m^3/kmol K
T : absolute temperature, K
t : storage duration, d (days) or s (seconds)
V : volume of package space, m^3
Y : constant number

Subscript
i : inside packages
s : food surface
ρ : outside packages
0 : initial

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