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# INFLUENCE OF EQUILIBRIUM MOISTURE CONTENT DATA ON RESULTS OF VEGETABLE DRYING SIMULATION

*Agnieszka Kaleta, Krzysztof Górnicki*

*Faculty of Production Engineering, Warsaw University of Life Sciences, Warsaw*

Key words: moisture sorption isotherm, equilibrium moisture content, drying, mathematical model, vegetable

Drying is one of the oldest and most important food preservation techniques involving moisture movement from the product to the drying air. The optimum design of drying and aeration and storage systems requires mathematical modelling using basic data on the moisture sorption behaviour of the material to be dehydrated. A large number of empirical, semi-empirical or theoretical models have been reported in the literature for describing moisture sorption isotherms of food materials. The reported work presents a review of literature on equations for fitting moisture sorption isotherms of several vegetables. Variation was shown in equilibrium moisture content values determined for the same product from different isotherm equations. Equilibrium moisture content data obtained from different equations were then used in a mathematical model of vegetable drying to simulate the process. Analysis of the results of simulation showed that the kind of equation of moisture sorption isotherm used in the model of vegetable drying influence the results of simulation. In conclusion it was suggested that an "overall – all" evaluation of this large number of isotherm equations is needed in order to have a more precise (and quantitative) definition of their fitting abilities as applied to different vegetables.

## ABBREVIATIONS

A, a, B, b, c, F, G, H, k, n, r – constants; $a_w$ – water activity; $Fo_m$ – Fourier number; R – gas constant, (J/(mole·K)); T – temperature, (K); u, $u_c$, $u_e$ – moisture content, critical moisture content, equilibrium moisture content, (kg $H_2O$/kg d.m.); $u_{e0.5}$ – equilibrium moisture content at $a_w$=0.5, (kg $H_2O$/kg d.m.); $u_m$ – monolayer moisture content, (kg $H_2O$/kg d.m.); $\tau$ – time, (s).

## INTRODUCTION

Drying is one of the oldest and most important food preservation techniques involving moisture movement from the product to the drying air. The optimum design of drying and aeration, and storage systems requires mathematical modelling. Models to describe drying processes are needed to enable scientific process design and minimization of energy and capital costs subject to quality constraints [Waananen *et al.*, 1993]. Hence, well verified mathematical drying models are necessary. The accuracy of predictions of drying processes using mathematical models is highly dependent on the completeness of the mathematical model and the relationships used to describe heat and mass transfer phenomena of a dried products. One such relationship is equilibrium moisture content (EMC). Its mathematical relationship is required so that it can be incorporated into a simulation model.

EMC is an important feature of food products which influences several aspects of drying and storage. A moisture sorption isotherm equation mathematically describes the relationship between the water activity and the equilibrium moisture content for a food product. Moisture sorption isotherms (MSIs) present an equilibrium state of all processes wherein water molecules combine reversibly with food solids. MSIs of biological materials when graphically expressed are nonlinear, generally sigmoidal in shape, and have been classified as type II isotherms by Brunauer [1945]. Some isotherms are of type III that behave parabolically or exponentially and certain food isotherms have an intermediate shape between types II and III [Iglesias & Chirife, 1981]. Another behaviour commonly exhibited by agricultural products is that different paths are followed during adsorption and desorption processes, resulting in a hysteresis effect.

Many investigators have reviewed isotherm equations in the literature but only several researchers have undertaken studies in an attempt to compare different MSI equations for goodness of fit [Chirife & Iglesias, 1978; Iglesias & Chirife, 1976a; Kaleta, 1996; Lomauro *et. al.*, 1985; Sun & Woods, 1993]. It turned out that at least seventy seven isotherm equations are available in the literature [van den Berg & Bruin, 1981]. Some of these equations have theoretical or half-theoretical backgrounds, others are simply empirical and the fitting abilities of those equations vary with the group of foods, some are suitable for starchy foods, some for vegetables and others for fruits.

The objective of this paper was to study the influence of equilibrium moisture content data on results of vegetable drying simulation.

Author's address for correspondence: Krzysztof Górnicki, Faculty of Production Engineering, Warsaw University of Life Sciences, ul. Nowoursynowska 164, 02-787 Warszawa, Poland; tel.: (48 22) 593 46 24; fax: (48 22) 593 46 27; e-mail: krzysztof_gornicki@sggw.pl

## MATERIALS AND METHODS

The following vegetables were considered in research: carrot, celery, onion, red beet, and sugar beet.

Sorption isotherm equations regularly cited in the literature to describe sorption behaviour of considered vegetables are reviewed in Table 1.

Constants for moisture sorption isotherm equations of considered vegetables mentioned in Table 1 were taken from the literature [Cenkowski *et al.*, 1992; Iglesias & Chirife, 1976a; Kiranoudis *et al.*, 1993; Lewicki, 2000; Lomauro *et al.*, 1985].

The mathematical model of drying of infinite plane was applied to simulate the process of vegetables drying. The equation which models the second drying period can be written as follows [Lykov, 1968]:

$$U(\tau)=\frac{u(\tau)-u_e}{u_c-u_e}=\sum_{n=1}^{\infty}B_n\exp\left(-\mu_n^2 Fo_m\right) \tag{1}$$

where $B_n=2/\mu_n^2$ and $\mu_n=(2n-1)\pi/2$.

For each vegetable in the consecutive simulation experiments different moisture sorption isotherm equation was considered in equation (1) and other parameters were taken as constant.

## RESULTS AND DISCUSSION

Moisture sorption isotherms of carrot are presented in Figure 1. Variation can be observed in equilibrium moisture content values determined for the same product from different isotherm equations. The most significant differences in EMC values were found for the water activity within the range of 0.2-0.7. It can be read off from Figure 1 that for example, for $a_w=0.5$ the lowest EMC value for desorption (0.11 kg $H_2O$/ kg d.m.) gives Halsey equation and the highest one (0.175 kg $H_2O$/ kg d.m.) gives Iglesias and Chirife equation. It means that equilibrium moisture content from IC equation is 1.59 times greater. As it is seen from Figure 1, the course of various moisture sorption isotherms for the same product is complicated. The isotherms intersect, run below or above each other, sometimes coincide. For example, for $a_w=0.3$ the lowest EMC value for desorption give both Halsey equation and Oswin equation and the highest one gives Iglesias and Chirife equation. For $a_w=0.65$ the situation is different. The lowest EMC value for desorption is obtained from Henderson equation, the highest one again from IC equation, GAB and Halsey equations give the same EMC value.

A similar character of differences in equilibrium moisture content determined from the discussed isotherm equations is obtained from adsorption.

The same trends were noticed for the other vegetables considered.

The results of application of equilibrium moisture content data obtained from different equations in the mathematical model of vegetable drying (1) to simulate the process are shown in exemplary Figures 2 – 4.

The course of the relative percentage deviation between the highest and the lowest value of the moisture content obtained from the mathematical model of carrot drying when various moisture sorption isotherms equations were applied is presented in Figure 2. It turns out that there is a discrepancy between the results of carrot drying simulation. The discrepancy increases with the passage of drying time and close to the end of the process the relative percentage deviation between the extreme values of the moisture content reaches almost 30%.

A comparison of the influence of particular moisture sorption isotherm equation on the results of carrot drying simulation is presented in Figures 3 and 4.

It can be stated that due to the variation in the MSI equation there is variation in the results of drying simulation. As it was noticed from Figure 1, the course of various moisture sorption isotherms for the same product is complicated. The isotherms intersect, run below or above each other, sometimes

TABLE 1. Sorption isotherm equations used in the work.

| Equation | Model | Model parameters | References |
|---|---|---|---|
| Guggenheim<br>– Anderson<br>– de Boer (GAB) | $u_e=\frac{u_m kca_w}{(1-ka_w)[1+(c-1)ka_w]}$ | c, k, $u_m$ | Anderson [1946];<br>de Boer [1953];<br>Guggenheim [1966] |
| Oswin | $u_e=A\left(\frac{a_w}{1-a_w}\right)^B$ | A, B | Oswin [1946] |
| Halsey | $a_w=\exp\left[-\frac{a}{RT(u_e/u_m)^r}\right]$ | a, r, $u_m$ | Halsey [1948] |
| Henderson | $1-a_w=\exp\left(-ku_e^n\right)$ | k, n | Henderson [1952] |
| Iglesias and Chirife (IC) | $\ln\left[u_e+\left(u_e^2+u_{e0.5}\right)^{0.5}\right]=Aa_w+B$ | A, B, $ue_{0.5}$ | Iglesias & Chirife [1976b] |
| Lewicki [1998] | $u_e=F\left[\frac{1}{(1-a_w)^G}-\frac{1}{1+a_w^H}\right]$ | F, G, H | Lewicki [1998] |
| Lewicki [2000] | $u_e=A\left(\frac{1}{a_w}-1\right)^{b-1}$ | A, b | Lewicki [2000] |

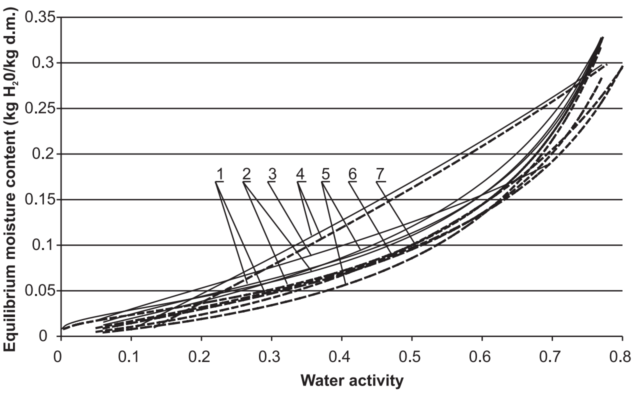

FIGURE 1. Moisture sorption isotherms of carrot by various workers; 1 – GAB, 2 – Halsey, 3 – Henderson, 4 – IC, 5 – Oswin, 6 – Lewicki [1998], 7 – Lewicki [2000], (—) – desorption, (– –) – adsorption.

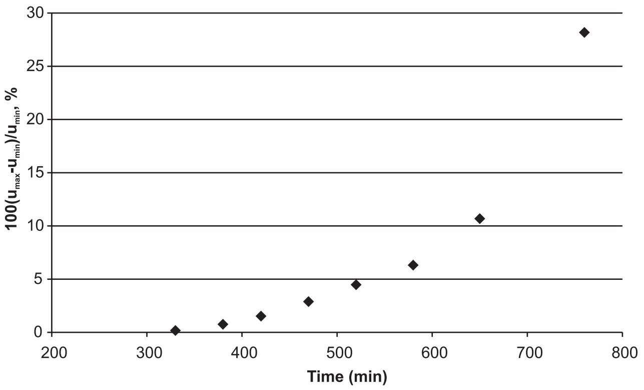

FIGURE 2. Influence of moisture sorption isotherm equation on the results of carrot drying simulation at $a_w = 0.6$.

coincide. Therefore it cannot be univocal ascertained which MSI equation used gives higher, which lower and which extreme values of the moisture contents obtained from the mathematical model of drying. It depends on water activity. The same results were noted for all vegetables considered.

## CONCLUSIONS

The analysis of the results of simulation showed that the kind of equation of moisture sorption isotherm used in the mathematical model of vegetable drying influences the results of simulation. The effect of MSI equation on the moisture contents computed from the mathematical model becomes stronger with drying time proceeding. The demonstrated effect should be taken into consideration during predictions of drying processes using mathematical models. Moreover it could be suggested that an "overall – all" evaluation of a large number of moisture sorption isotherm equations is needed in order to have a more precise (and quantitative) definition of their fitting abilities as applied to different vegetables.

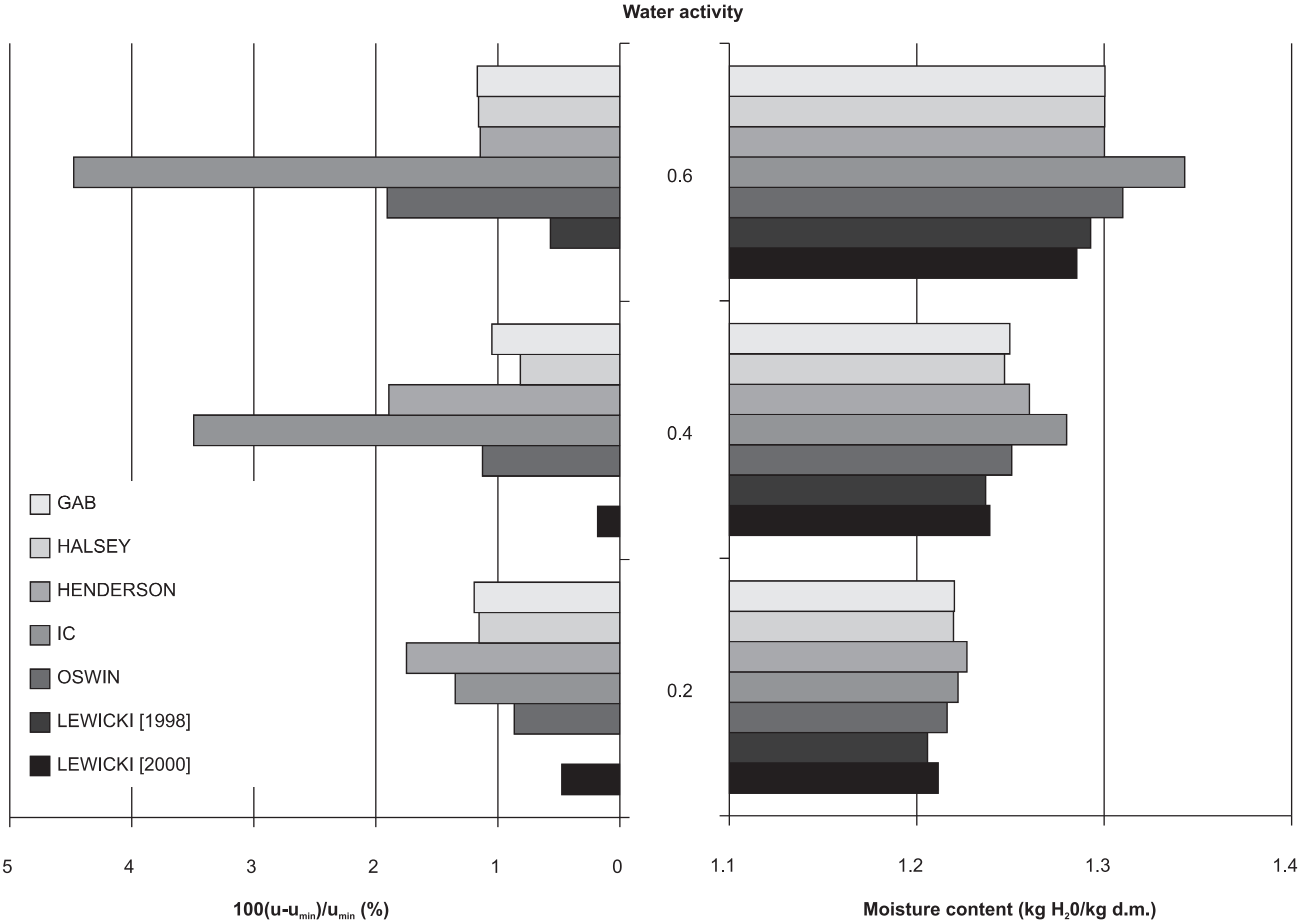

FIGURE 3. Influence of particular moisture sorption isotherm equation on the results of carrot drying simulation at 520th minute of drying.

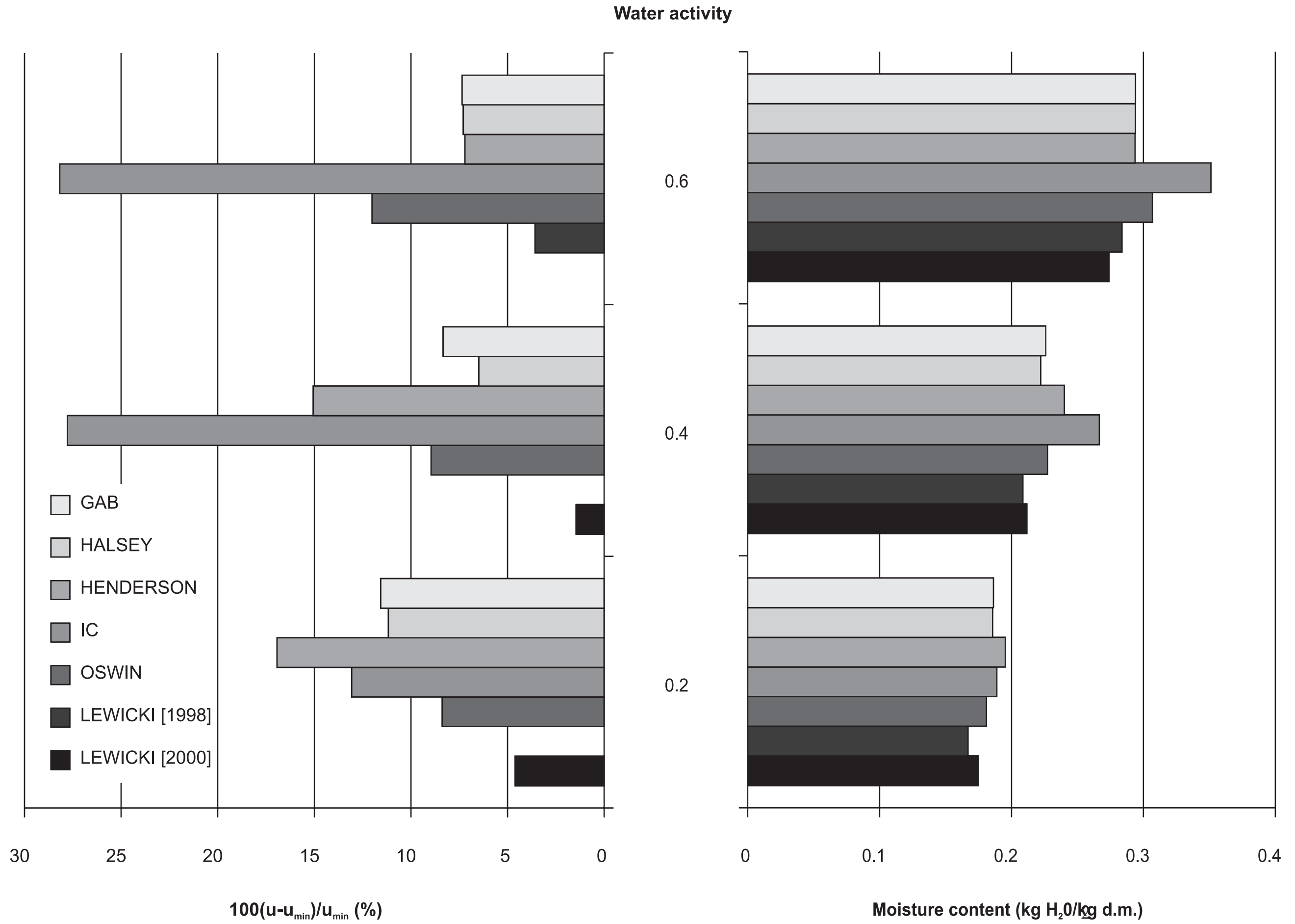

FIGURE 4. Influence of particular moisture sorption isotherm equation on the results of carrot drying simulation at 760th minute of drying.

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# WPŁYW RÓWNOWAGOWEJ ZAWARTOŚCI WODY NA WYNIKI SYMULACJI PROCESU SUSZENIA WARZYW

*Agnieszka Kaleta, Krzysztof Górnicki*

*Wydział Inżynierii Produkcji, Szkoła Główna Gospodarstwa Wiejskiego, Warszawa*

Projektowanie optymalnych systemów suszenia, przewietrzania i przechowywania produktów żywnościowych wymaga znajomości matematycznych modeli opisujących te procesy. Jedną z bardzo ważnych danych niezbędnych do przeprowadzenia symulacji jest równowagowa zawartość wody. W pracy przedstawiono przegląd najczęściej stosowanych formuł empirycznych oraz modeli semi-empirycznych i teoretycznych do wyznaczania izoterm równowagi suszarniczej marchwi, selera, cebuli, buraków ćwikłowych i buraków cukrowych. Na przykładowym rysunku 1 pokazano, że wartości równowagowej zawartości wody wyznaczone dla tego samego produktu z różnych równań izoterm równowagi suszarniczej mogą znacznie różnić się od siebie. Wartości równowagowej zawartości wody wyznaczone z różnych izoterm równowagi suszarniczej wykorzystano następnie w matematycznym modelu suszenia omówionych warzyw. Analiza uzyskanych wyników symulacji, przedstawionych na przykładowych rysunkach 2 – 4, pokazała, że rodzaj równania równowagi suszarniczej zastosowanego w matematycznym modelu suszenia ma wpływ na wynik symulacji. Wpływ ten wzrasta z upływem czasu suszenia. Pod koniec procesu względny procentowy rozrzut pomiędzy największą i najmniejszą wartością wyznaczonej z modelu suszenia zawartości wody osiąga prawie 30%. Zasugerowano potrzebę dalszych badań, które miałyby na celu określenie, które z licznych równań równowagi suszarniczej zastosowane w matematycznym modelu suszenia warzyw pozwoliłby na opisanie przebiegu suszenia z dużą dokładnością.