Sorption and desorption isotherms of celery roots

Mariya Georgieva[1,*], *Ivan* Kiryakov[1], *Dimitar* Atanasov[1] and *Atanas* Tashev[1]

[1]University of Food Technologies – Plovdiv, Department of Industrial Heat Engineering, 4002 bul. "Maritza" 26, Bulgaria

Abstract. An experimental study for determining the wet basis equilibrium moisture content in celery root (Apium graveolens) was conducted. Empirical equations describing the isotherms of sorption and desorption of the product at a temperature of 20°C were obtained. The values for the wet basis equilibrium moisture content for higher temperatures – 40, 60 and 80°C were theoretically calculated. All results were summarized in analytical, graphical and tabular form.

1 Introduction

Drying is an important heat and mass transfer process that finds wide application in the food industry. The objects of drying are variety of wet materials in various stages of their processing, such as raw materials, semi-finished products and finished products. Food products have been characterized by a number of features - they are non-isometric, diverse in composition and structure, contain many active components, differ in color, origin, etc.

On the basis of colloidal-physical properties, A.V. Likov [3] has divided solid wet materials into three groups - colloidal, capillary-porous and capillary-porous colloidal. Most food products belong to the last group.

For conducting a drying process, an information for a number of properties of the product is needed like a moisture content, thermo-physical parameters, sorption (desorption) properties, kinetic dependencies, etc.

The aim of the present study is to experimentally determine the wet basis equilibrium moisture contents (EMC (w.b.)) and to plot the sorption and desorption isotherms of celery root, as well as to obtain the corresponding analytical dependences.

2 Materials and methods

During the drying process or in long-term storage, the products are exposed to heat, steam and liquids. Of greatest practical interest is the effect of heat and water vapor (hygrothermal treatment), as well as the hygrothermal equilibrium state of the material, i.e., the condition of equilibrium between the product and the surrounding humid air.

In this state of equilibrium, the temperature of a material is equal to the temperature of the air, and the water vapor pressure in it P_M is equal to the partial pressure of water vapor in the air. The moisture content (wet or dry basis) of the colloidal capillary-porous product assumes some constant value, called equilibrium moisture content.

The equilibrium moisture content of the material depends on the temperature, on the humidity of the surrounding air and on the way of achieving the equilibrium state (sorption or desorption).

If a thermodynamic system "wet product - humid air" is not in equilibrium state, two different transfer processes are possible:

- If $P_M > P_A$ - the product gives off moisture, the balance can be achieved through desorption or drying;
- If $P_M < P_A$ - the product absorbs moisture, the equilibrium condition can be achieved through sorption or moistening.

Generally, the water vapor content in the air are characterized by the relative humidity φ.

The dependence between the EMC (w.b.) and the vapor pressure in the material can be obtained by changing the relative air humidity at a constant temperature. It can be presented in the form of a curve called an isotherm $- W_p = f(\varphi)$ at $t = \text{const}$. If the equilibrium states are reached by sorption, the isotherm is called a sorption isotherm. If they are reached by desorption, a desorption isotherm respectively.

In a state of equilibrium, the product's moisture content is the same throughout its volume, and its temperature is equal to that of the surrounding air.

The procedure described above is the basis of the so-called tensimetric method for taking equilibrium isotherms, which is lengthy but provides high measurement accuracy

The method consists of the following: 3 to 5 g of the product is placed in weighing glasses and placed in a glass vessel (desiccator) in which a constant temperature (20°C) and constant relative humidity are maintained. The sample is periodically weighed until a constant mass is

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*Corresponding author: m_georgieva@uft-plovdiv.bg reached and the EMC (w.b.) is determined by the weight method. The product in the weighing glasses was dried in an atmospheric drying chamber at a temperature of 100 + 2°C until reaching a constant mass (absolutely dry product). An analytical balance with an accuracy of 0.0001 g was used to accurately determine the mass of the product.

Different relative humidity of the air was maintained using saturated aqueous solutions of salts in eight desiccators. Table 1 shows the salts used in the experiment and the relative air humidity they maintain at a temperature of 20°C.

Table 1. Salts used in the experiment and the relative humidity they maintain at a temperature of 20°C

Salts	**φ, %**	**Salts**	**φ, %**
NaOH	6.98	K_2CO_3	43.9
LiCl	11.14	NaBr	58.7
CH_3COOK	23.1	NaCl	75.4
$MgCl_2$	32.1	Na_2SO_4	86.9

From experimental results obtained at a temperature of 20°C, mathematical dependences of the type $W_p = f(\varphi)$ - equation (1) were derived using the standard statistical program Table Curve 2D v.5.01. From the resulting equations describing the sorption and desorption isotherms, the EMC (w.b.) values of celery root were calculated for relative air humidity from 10 to 90%. For practice, it is of interest to know the sorption and desorption isotherms for a wider temperature interval. On the basis of the experimentally obtained EMC (w.b.) at 20°C, analogous equations for higher temperatures (40, 60 and 80°C) were derived theoretically. For this purpose, the Pass and Slepchenko’s method was used [1]. It gives good results for various materials in the temperature range (-20) ÷ (+100°C). Using the resulting equations, the EMC (w.b.) of the product was calculated for the same values of relative air humidity.

3 Results and discussion

The results for the EMC (w.b.) of celery roots are presented in table 2 and table 3. The values for 20°C were obtained experimentally, and those at 40, 60 and 80°C were determined theoretically.

In addition to tabular and graphical form, EMC (w.b.) can be calculated using analytical relationships (equations) describing sorption and desorption isotherms. A large number of factors influence the sorption process. For this reason, until recently it was not possible to describe the equilibrium curves with a single equation. Therefore, there are a large number of equations (empirical and semi-empirical) in practice, valid within narrow limits of relative air humidity. However, this requires an equilibrium isotherm to be described by several equations. The most commonly used equations are of BET (Brunauer, Emmett and Teller) or GAB (Guggenheim, Anderson and De Bohr) type [3]. Although they have a theoretical basis, their main drawback is that they contain constants that must be determined experimentally. These problems have already been solved using modern computer technologies.

Table 2. EMC (w.b.) -W_p, % of celery roots, determined by sorption at different temperatures

Relative air humidity	Temperature, °C			
	20	40	60	80
10	5.174	4.076	3.171	2.487
20	7.933	6.632	5.608	4.675
30	9.834	8.549	7.597	6.645
40	11.43	10.24	9.367	8.485
50	13.05	11.99	11.11	10.30
60	15.09	14.12	13.10	12.25
70	18.36	17.25	15.82	14.71
80	26.11	23.15	20.91	18.99
90	44.95	41.32	39.55	37.15

Table 3. EMC (w.b.) - W_p, % of celery roots, determined by desorption at different temperatures

Relative air humidity	Temperature, °C			
	20	40	60	80
10	5.173	3.830	3.099	2.452
20	8.197	6.699	5.654	4.708
30	10.39	9.013	7.862	6.820
40	12.27	11.05	9.893	8.857
50	14.16	13.04	11.92	10.92
60	16.47	15.29	14.19	13.17
70	20.06	18.47	17.24	16.03
80	28.11	24.86	22.73	20.82
90	74.30	58.19	41.91	37.73

The resulting analytical dependences describing the sorption and desorption curves have the following form:

$$W_P = \frac{a+c\varphi+e\varphi^2}{1+b\varphi+d\varphi}, \qquad (1)$$

where: φ - Relative air humidity, %;

W_p - EMC (w.b.), % ;

a, b, c, d and *e* - coefficients whose values are given in the table 4 and table 5. The correlation coefficients r^2 and the average statistical error are indicated in the same tables.

The resulting equations are applicable in the range $0 < \varphi < 0.9$.

Table 4. Coefficients for the sorption equation

Coefficients	Temperature,°C			
	20	40	60	80
a	0.029765422	-0.06022424	-0.069605154	-0.008991323
b	0.040333197	0.029260165	0.00993754	-0.001760166
c	0.76152322	0.55750121	0.38181602	0.2686481
d	-0.00055229934	-0.0003975413	-0.00020992203	-9.268959×10^{-5}
e	-0.006700531	-0.0040785715	-0.0032865896	-0.0025673976
r^2	0.9985216	0.9994921	0.9996588	0.9997727
Fitt Std Err	0.754736	0.40252992	0.32993334	0.26929031

Table 5. Coefficients for the desorption equation

Coefficients	Temperature,°C			
	20	40	60	80
a	0.14686937	-0.035266845	-0.016523139	-0.01329563
b	0.028920972	0.010213605	0.0037107219	-0.0040417157
c	0.69043148	0.45889164	0.34911966	0.25916332
d	-0.00042397023	-0.00022098163	-0.00014498	-6.6349172×10^{-5}
e	-0.0060170846	-0.0041656984	-0.0030512153	-0.0024175805
r^2	0.9961734	0.9999624	0.9998879	0.9998846
Fitt Std Err	1.2372217	0.18718606	0.32301286	0.32784984

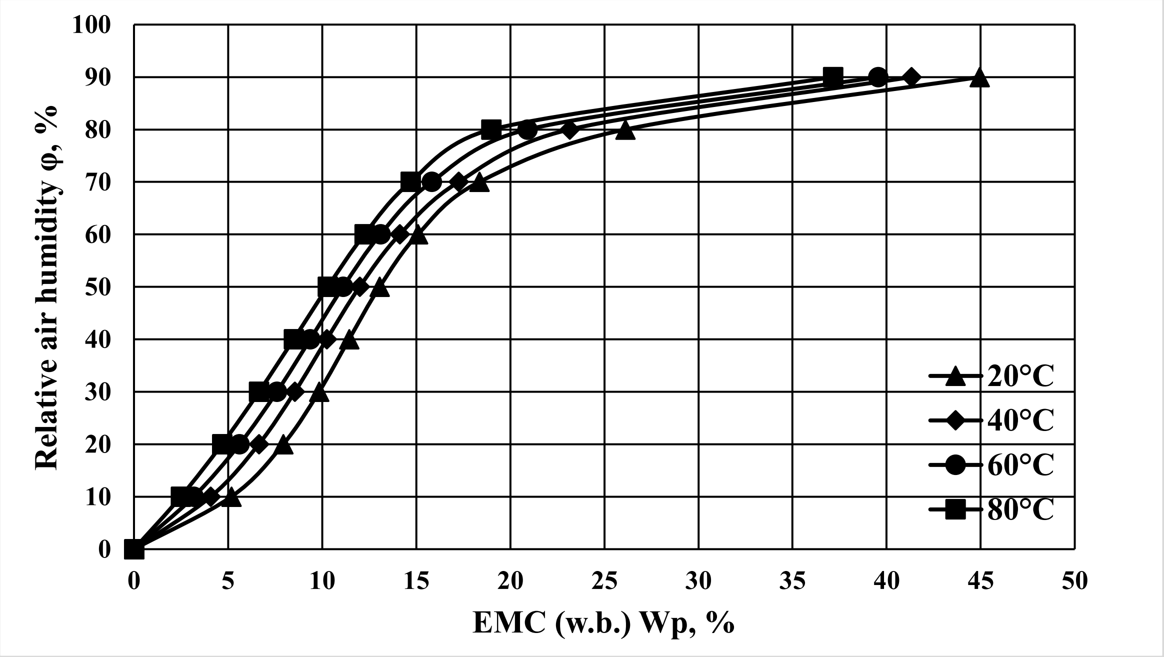

Fig.1. Sorption isotherms of celery roots at different temperatures

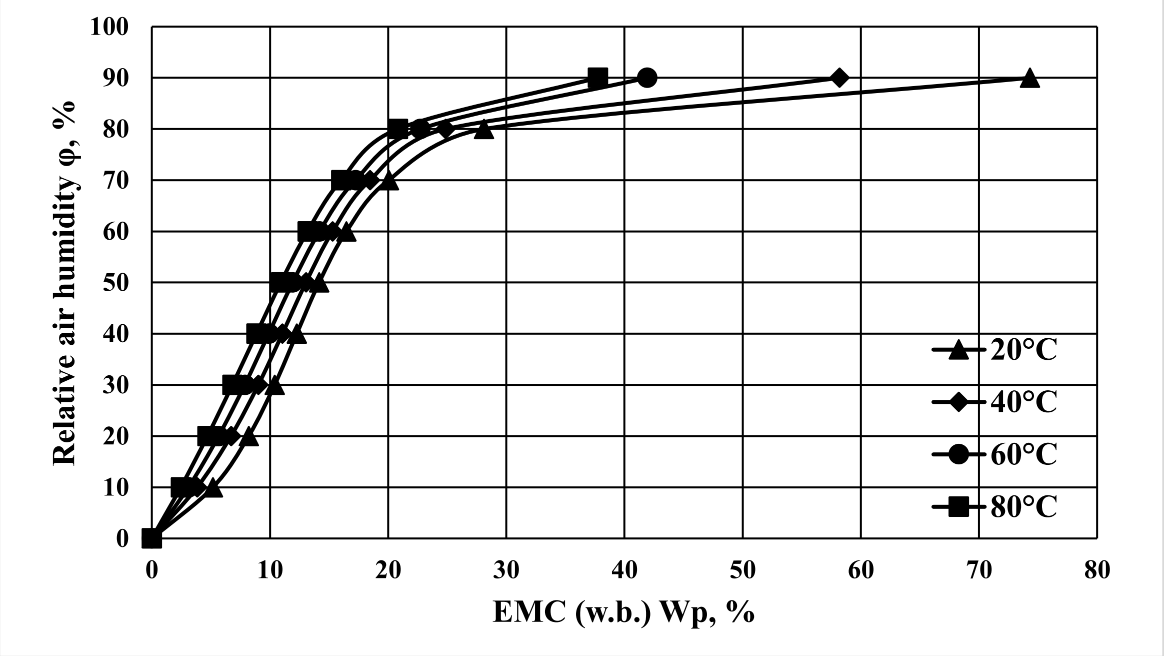

Fig.2. Desorption isotherms of celery roots at different temperatures

The graphs in fig. 1 and fig. 2 are constructed from the data, presented in table 2 and table 3. As can be seen, as the temperature increases, the equilibrium isotherms shift to the left in the entire temperature range. There is a clearly expressed sorption hysteresis in the entire temperature range.

From the equilibrium curves, information about the type of binding of the water and the material can be obtained.

It can be seen that the isotherms of the celery roots have an ***S***-shaped character. According to the theory of drying, this means that the binding of moisture to the material is carried out in three ways - monomolecular adsorption, polymolecular adsorption and capillary condensation. For monomolecular adsorption can be judged by the convex part of the curve towards the abscissa axis. To determine the adsorption-bound moisture of the monomolecular layer, Filonenko's method can be used [6] The reading is made from the abscissa axis, from the point where the continuation of the middle part of the sorption curve crosses it ($W_{\mathrm{p}} = 5\%$ at 20°C). The value decreases with increasing the temperature. The middle part of the curves have an approximately linear character, which indicates that the binding is by the mechanism of capillary condensation. At high relative air humidity values, the convex part is towards the ordinate axis, which means that polymolecular adsorption exists.

4 Conclusion

Experimental studies were conducted to determine the EMC (w.b.) of celery roots. The obtained results are useful in practice in the design of drying processes and devices and are presented:

- in tabular form - table 2 and table 3;
- in graphic form - fig. 1 and fig. 2;
- in analytical form - equation (1), table 4 and table 5.

The final results obtained are valid in the following ranges:

- relative humidity $0 < \varphi < 0.9$ $(0\ \% < \varphi < 90\ \%)$
- temperature t = 20 ÷ 80°C.

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