

Moisture adsorption behaviour of semolina and farina

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Received 2 May 2003; revised 9 July 2004; accepted 14 July 2004

Abstract

Moisture adsorption isotherms of semolina (from hard wheat) and farina (from soft wheat) were determined at 20, 35, 50 and 60°C using the isopiestic method. The adsorbed moisture content significantly affected ($p < 0.05$) product type, temperature and water activity. Moisture up-take accelerated about 0.75 water activity. The experimental sorption data obtained in this study were applied to Halsey, Harkins-Jura, Henderson, Iglesias-Chirife, Smith BET, GAB isotherm equations to predict the sorption behaviour of semolina and farina. Henderson, Halsey and GAB equations were found to be the most suitable model to describe the isothermal water sorption of semolina and farina at 0.1–0.9 water activity range. Monolayer moisture contents (m_0) for two products were calculated from BET and GAB equations. The m_0 values of both models decreased with increasing temperature. The values of m_0 of semolina and farina at 20°C were 11.8 and 9.16 g/100 g calculated with GAB, respectively. Adsorption isosteric heat (Q_s) decreased; the maximum heat of adsorption was obtained in the moisture content 6–7% and was higher for semolina (15.2 kJ/mol) than farina (14.34 kJ/mol). The Q_s value quickly decreased with increase in moisture content to approximately 15% and then was plateau on axis of moisture content. Semolina and farina must be storage below 75% relative humidity at 20°C prevents caking and deterioration because moisture sorption acceleration was increased after 0.75 a_w . The moisture content of the products in this storage conditions could be approximately 12.5%.

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Keywords: Semolina; Farina; Adsorption isotherm; Monolayer moisture content

1. Introduction

Semolina is coarsely-ground hard wheat (*Triticum durum*), while farina is coarsely-ground ground soft wheat (*Triticum aestivum*). Semolina is the preferred flour component for many pasta formulations and commonly used to make short pasta such as rigatoni, long pasta like spaghetti and couscous. Farina, made from cereal grains, is a bland-tasting flour or meal that, when cooked in boiling water, makes a hot breakfast cereal. Although durum wheat is considered the best raw material for pasta production, the use of farina from nondurum wheat is per-

mitted in Canada and the United States and largely depends on the availability and price of durum semolina (Malcolmson, Matsuo, & Balshaw, 1993). Both semolina and farina are very easily digested and rich in protein.

The water molecule is highly polar because of asymmetry of electrical charges and has a vapour-state dipole moment. The polarity produces intermolecular attractive forces between water molecules and other polar organic groups of food components (Fennema, 1985).

Water vapour sorption isotherms have a number of very important applications in food science and technology. They present an equilibrium state of all process wherein water molecules combine reversibly with food solids (Lewicki, 2000). The knowledge of moisture sorption characteristics for these products would allow correctly specifying the conditions of storage,

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and packaging, and predicting shelf life, and understanding the physicochemical changes involved in product making process. It is not expected that semolina and farina will have the same behaviour due to the differences in major components and origin. A number of papers have been published on the equilibrium sorption properties of wheat flours, but no significant data is available for semolina (Hebrard et al., 2003) and especially farina.

They also provide an easy way to evaluate physical, chemical and microbiological parameters suitable and deteriorative reactions for the determination of stability of dry foods (Leiras & Iglesias, 1991). Moisture sorption isotherms have been used to explain the relation between water content of food and equilibrium relative humidity of atmosphere surrounding the food and to obtain information about the mechanism of water binding during sorption in foods. In the other words, the mathematical relation between water content of food and equilibrium humidity at constant temperature has been described as moisture sorption isotherm (Labuza, 1984; Lomauro, Bakshi, & Labuza, 1985).

In addition to moisture sorption isotherms, isotherm equations are also commonly used in the prediction and modelling of the determination of packing, storage parameters, evaluating properties of dry mixes and shelf life of the products, and the determination of drying conditions and times (Andrieu, Stamatopoulos, & Zafiropoulos, 1985; Chirife & Iglesias, 1978; Ertugay, 1996; Labuza, 1984). In most cases the sorption data are obtained at one temperature, usually the temperature of storage, but for the thermodynamic analysis of sorption and to model the storage stability processes, it is necessary to know the isotherms in a range of temperatures. Important thermodynamic parameter is the isosteric heat of sorption which measures the binding energy or the force between water vapour molecules and the polar (active) sites of adsorbent surfaces (Labuza, 1984). Additionally, equations for fitting moisture sorption isotherms are available for the analysis of dehydration and subsequent conservation of food stuffs (Lagoudaki, Demertzis, & Kontominas, 1993). Therefore, the numerous models have been studied for describing the sorption characteristics of foods. An increasing number of works have been reported in this area recently (Ajibola, Aviara, & Ajetumobi, 2003; Chen, 2003; Debnath, Hemavathy, & Bhat, 2002; Ertugay & Certel, 2000; Hebrard et al., 2003; Menkov, 2000a; Menkov & Gelyazkov, 2000; Sandoval & Barreiro, 2002; Sogi, Shivhare, Garg, & Bawa, 2003).

The objective of this study was to determine the moisture sorption isotherms of semolina and farina at 20, 35, 50 and 60 °C, to investigate the applicability of various isotherm equations to the sorption data obtained at these temperatures, to evaluate and compare monolayer moisture content (m_0) obtained with BET and GAB equations and to determine the adsorption isosteric heat of these products.

2. Materials and methods

2.1. Materials

In this research, commercial semolina (125–800 µm, mainly composed of three sieve (Retsch, Haan, Germany) particles: <125 µm 10%, 125–500 µm 80%, 500–800 µm 10%) (*T. durum*) and farina (125–800 µm, similar particles size) (*T. aestivum*) samples produced in accordance with 2002/21 number of Turkish Food Codex (İrmik Tebliği, 2002) were obtained from local supermarkets in Antalya, Turkey. All chemicals used in chemical analysis and the preparation of saturated salt solutions were reagent grade.

2.2. Methods

2.2.1. Chemical analysis

Protein, starch, ash, fat and raw cellulose contents of samples on dry matter basis were determined according to AACC approved methods (*Approved methods of the AACC*, 2000).

2.2.2. Determination of sorption isotherms

An isopiestic method was employed for the determination of the sorption isotherms by exposing the samples to atmospheres of known relative humidities at different temperatures (20, 35, 50 and 60 °C) (Benado & Rizvi, 1985; Gal, 1975; Labuza, 1984). For the adsorption process, samples were first dried to a level containing 3% water contents for sorption in a vacuum oven (Shel-lab VWR scientific, Cornelius, USA) (in 150 mmHg, at 35 °C), and samples of 50 mg were sensitively 0.1 mg weighed (Chyo JL-200, Japon) into Quick-fit® glass bottles that are beforehand balanced at the 0.2–0.9 water activity and studied temperature. The weighing bottles, as triplicate for each product, were then put into desiccators containing eight different saturated salt solutions providing relative humidities between the values of 20% and 90%. The bottles were weighted every day because of determination time of dynamic equilibrium, and reached a constant weight up to four days. These glass bottles were kept half-open in desiccators containing various salt solutions that provided the desired relative humidity for five days, so that the samples could reach to the same moisture levels with the atmosphere surrounding samples, as known equilibrium moisture content. The bottles were then taken from desiccators and their weight gains were determined by weighing closed bottles. The study was carried out two replicates. The saturated salt solutions used in this study were prepared a week beforehand and allowed to gain stability at 80 °C by mixing everyday.

The saturated salt solutions and relative humidity media were CH₃COOK 23.11%, MgCl₂ 33.07%, KCO₃ 43.16%, MgNO₃ 54.38%, NaBr 59.14%, NaCl 75.47%,

KCl 85.11% and BaCl₂ 90.69% at 20°C (Certel, 1990; Labuza, 1984). The equilibrium relative humidity values in the ambient inside the desiccators were controlled by using electronic relative humidity meter. Moreover, to inhibit mould growth a small dish containing 1 ml of toluene (75%) was also placed into the desiccators, which had a range 0.5–0.9 water activity (McMinn & Magee, 1999).

2.2.3. Fitting of sorption data to various isotherm equations and determining of sorption isosteric heat

Experimental data were applied to seven different isotherm equations: Halsey, Henderson, Harkins-Jura, Iglesias-Chirife, Smith, BET (Brunauer, Emmet and Teller) and GAB (Guggenheim, Anderson and de Boer). The constants for isotherm equations were calculated using linear regression and differently non linear regression for GAB.

The goodness of fit of the different models was evaluated with the mean relative deviation (*E*%) between the experimental (*m_e*) and calculated (*m_c*) moisture content. Where *n* is number of observations (Andrieu, Stamatopoulos, & Zafiropoulos, 1986; Lomauro et al., 1985).

$$E\% = \frac{100}{n} \sum_{i=1}^n \left| \frac{m_{ei} - m_{ci}}{m_{ei}} \right|$$

The isosteric heat of adsorption (*Q_s*) was calculated from integrated form of Clausius–Clapeyron equations (Iglesias, Chirife, & Fontan, 1989). Where *R*, *T* and *a_w* are ideal gas constant, temperature and water activity, respectively.

$$Q_s = R \times \left[\frac{T_1 \times T_2}{(T_2 - T_1)} \right] \times \ln \left(\frac{a_{w2}}{a_{w1}} \right)$$

3. Results and discussion

3.1. Chemical characteristics of semolina and farina

Chemical characteristics of semolina and farina samples used in this study are presented in Table 1. Andrieu et al. (1986) reported that starch, protein and lipid of drum wheat semolina were 70, 14.5 and 2 g/100 g (w.b), respectively. Starch and protein contents of semolina and farina are relatively high that might be regarded as carbohydrate and protein source.

3.2. Sorption isotherms

The moisture sorption isotherms obtained from sorption data of the samples at 20, 35, 50 and 60°C are shown in Fig. 1. The moisture sorption isotherms of semolina and farina were characteristic of the type II isotherm, which is generally referred to as sigmoid isotherms or S type according to IUPAC classification (Rouquerol, Rouquerol, & Sing, 1999). The other researchers have also obtained the same results (Hebrard et al., 2003; Lagoudaki et al., 1993). In general wheat and its products have type II isotherms (Hebrard et al., 2003). Physical adsorption on microporous solids can result in type II isotherms, and correspond to multilayer formation (Adamson, 1990). Therefore, these

Table 1
Chemical characteristics^a of semolina and farina samples

Variety	Starch	Protein	Crude fibre	Ash	Ether extract
Semolina	73.64	15.35	7.05	0.772	1.09
Farina	77.05	13.96	5.51	0.554	0.92

^a Values are expressed as % on dry basis.

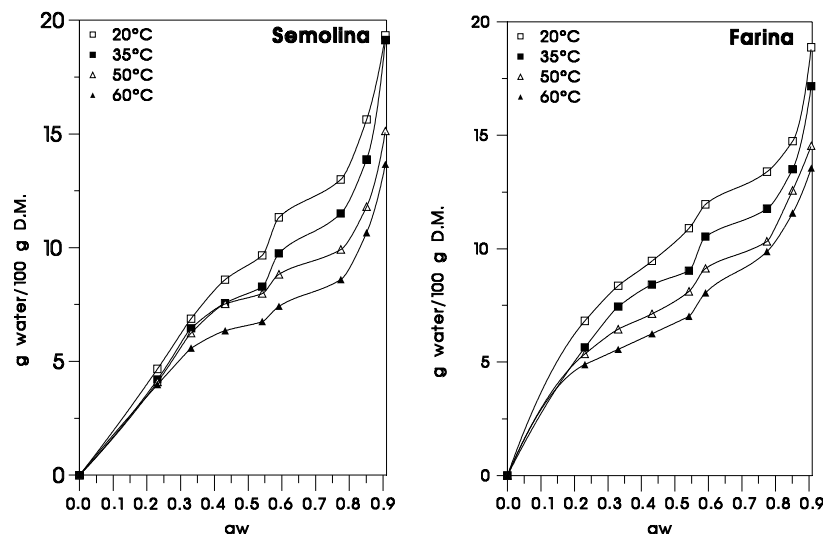


Fig. 1. Moisture adsorption isotherms of semolina and farina at 20, 35, 50 and 60°C.

sorption isotherm curves of the samples indicated that sorption occurred in semolina and farina, starchy products, was multilayer adsorption (Ertugay & Certel, 2000; Sopade & Ajisegeri, 1994).

The equilibrium moisture contents, the sorption isotherms, were significantly affected ($p < 0.05$) by product type (semolina and farina) and temperature at each water activity by analysis of variance (Table 2).

The equilibrium moisture content increased at the same a_w as temperature decreased, or at the same equilibrium moisture content, a_w increased as temperature increased (Fig. 1). The samples adsorbed more water at low temperatures than at high temperatures. The reason may be because water molecules at lower temperatures have a lower kinetic energy which is not enough to overcome the corresponding sorption energy (Lagoudaki et al., 1993). Furthermore, water molecules are bound polar sites of the food components, such as starch, protein and cellulose, and adsorbed water molecules by hydrogen bound. The formation of the hydrogen bonds is an exothermic reaction (Levine, 1995). So, it is possible that an exothermic reaction decreases as the temperature increases. Similar results also were obtained in some other studies (Achoba, Elegbede, Agbaji, & Agbaji, 1991; Andrieu et al., 1986; Ayrancı, Ayrancı, & Doğan, 1990; Certel & Ertugay, 1997; Chen, 2003; Debnath et al., 2002; Igbeka & Blaisdel, 1982; Inglett & Munck, 1980; McMinin & Magee, 1999; Rovedo, Roberto, & Constantino, 1993; Sopade & Ajisegeri, 1994; Tsami, Marinou-Kouris, & Maroulis, 1990). Moisture sorption of semolina and farina increased with increasing a_w value but that sharply increased after $0.75a_w$. That might be reasoned capillary condensation.

Hebrard et al. (2003) reported that changes in temperature (25, 35 and 45°C) seem to have no effect on the water at constant equilibrium relative humidity for semolina; but temperature effects in our study was found significant.

Since the samples are rich in protein and starch, these components affect the sorption data increasingly, because protein and starch as macromolecules are rich in polar sites such as –OH and –H groups, which behave a active (polar) sorption centres. According to the obtained moisture sorption data, semolina had lower sorp-

tive capacity than that of farina in 0.2–0.9 water activity range at all temperatures. The reason may be because semolina contained higher protein and harder than that of farina. Therefore diffusion of water into semolina might be obstructed. Additionally, it is possible that damaged starch content of farina might be high than semolina because of different milling process; although, starch damage is directly related to wheat hardness and the hard wheat shows higher starch damage than the soft wheat after same milling (Mok & Dick, 1991a, 1991b). Damaged starch of semolina has been 5.9% (Hebrard et al., 2003). It is reported that the particle size distribution of semolina had no significant influence on the isotherm (Andrieu et al., 1985). Particle size of semolina is not effect on the amount of sorption water, but effect on sorption rate (Hebrard et al., 2003).

3.3. Fitting of sorption data to various isotherm equations and isosteric sorption heat

The data obtained were applied to seven different sorption equations in order to determine the best model to predict the sorption behaviour for the products investigated accordingly to $E\%$. Johnson and Brennan (2000) reported that $E\%$ values below 10% as indicating a very good fit for practical purpose. The results obtained are presented in Table 3.

The fitness of sorption equations to experimental sorption isotherms of semolina and farina were realized average $E\%$ of all temperature and related a_w range, and were acceptable Henderson (6.74%), Halsey (6.81%), Smith (7.05%), Iglesias-Chirife (7.47%), BET (9.42%), GAB (9.93%), respectively except for Harkins-Jura (27.3%). In general, the equations better fitness to farina than semolina. It might be reason from high starch content of farina and it's soft for water diffusion.

It may be concluded that Henderson equation, the most widely used model, is the most suitable to describe the isothermal water sorption of semolina and farina in the 0.2–0.9 water activity. The goodness of fit for Henderson equation indicate the stability of the starchy products (Andrieu et al., 1985) and the microporous structure to moisture sorption; the microporous structure is more stable (Boki & Ohno, 1991). Regarding these values, it can be stated that the microporous structure of semolina and farina are more stable. The Henderson equation was the most suitable to describe the sorption behaviour starchy foods (Sopade & Ajisegeri, 1994). The Halsey equation provides an expression for condensation of multilayers (Chirife & Iglesias, 1978). The good fitness of Halsey equation is indicating for multilayers sorption of semolina and farina. The Smith equation seems to fits quite well with the data in the 0.2–0.8 water activity range. High W_b values in the Smith equation are also regarded as the high sorptive capacity of the adsorbents. As shown in Table 3, gener-

Table 2
Analysis of variance for equilibrium moisture content

Source	Degree of freedom	Mean square	F
Product (P)	1	12.57	20.38**
Temperature (T)	3	62.01	100.52**
Water activity (a_w)	7	222.68	360.97**
$P \times T \times a_w$	52	1.53	2.48**
Error	64	0.62	

** $p < 0.01$.

Table 3

Applicability of isotherm equations to moisture sorption data of semolina and farina and their constant parameters

Isotherm equations	a_w range	Constants	Semolina				Farina			
			20°C	35°C	50°C	60°C	20°C	35°C	50°C	60°C
Halsey: $\ln m = \frac{1}{n} \ln c - \frac{1}{n} \ln \left[\ln \left(\frac{1}{a_w} \right) \right]$	0.3–0.9	$E\%$	10.32	7.27	9.28	4.66	7.21	6.34	5.30	4.17
		n	2.18	2.16	2.72	2.55	3.11	2.76	2.72	2.78
		c	72.36	58.87	151.8	74.05	889.0	251.1	170.2	174.9
Henderson: $\ln[-\ln(1 - a_w)] = \ln k + n \ln m$	0.2–0.9	$E\%$	6.73	6.90	7.90	7.09	7.70	6.48	4.85	6.32
		n	0.016	0.018	0.009	0.013	0.022	0.005	0.017	0.006
		k	1.71	1.72	2.13	2.09	2.43	2.20	2.17	2.24
Harkins-Jura: $\frac{1}{m^2} = \frac{B}{A} - \frac{1}{A} \ln a_w$	0.2–0.8	$E\%$	33.76	33.81	29.96	22.11	26.70	22.31	23.96	25.86
		A	15.90	15.2	15.5	14.1	35.2	24.3	20.5	20.4
		B	0.056	0.034	0.001	0.052	0.046	0.035	0.044	0.062
Iglesias-Chirife: $\ln[m + (m^2 + m_{0.5})^{1/2}] = p + ba_w$	0.2–0.6	$E\%$	8.34	9.32	9.14	7.61	14.85	9.76	6.97	14.77
		B	1.71	0.91	0.72	0.73	0.3	0.69	0.67	0.73
		P	2.05	2.36	2.41	2.41	2.74	2.57	2.45	2.30
Smith: $m = W_b - W[\ln(1 - a_w)]$	0.2–0.8	$E\%$	9.08	7.91	10.89	5.31	7.70	6.74	4.71	4.10
		W	6.18	6.08	4.35	3.97	4.97	4.75	4.09	4.02
		W_b	4.43	3.49	4.22	3.57	6.42	5.29	4.76	3.98
BET: $m = \frac{m_0 C a_w}{(1 - a_w) + (C - 1)(1 - a_w) a_w}$	0.2–0.6	$E\%$	5.78	6.48	7.12	15.21	7.78	7.19	9.68	16.14
		m_0	5.40	4.32	4.21	3.07	5.28	4.39	3.78	3.50
		C_B	7.45	20.29	20.39	23.25	120.0	75.82	29.82	18.04
GAB: $m = \frac{m_0 C k a_w}{(1 - k a_w)(1 - k a_w C k a_w)}$	0.2–0.9	$E\%$	20.11	7.37	11.17	9.63	14.74	7.23	3.80	5.36
		m_0	11.8	6.45	5.92	3.53	9.16	6.01	5.23	4.76
		k	0.65	0.71	0.72	0.76	0.65	0.69	0.71	0.73
		C_G	4.21	8.77	10.01	200.1	14.06	31.95	37.04	137.0

m : Equilibrium moisture content (g/100 g); a_w : water activity; m_0 : monolayer moisture content; $m_{0.5}$: moisture content at $0.5a_w$; n , C , C_B , C_G , A , B , W , W_b , k , p and b are constant parameters for the isotherm equations; $E\%$: mean relative deviation.

ally, the sorptive capacity of the adsorbents decreased as the temperature increased. Also, the sorptive capacity of farina was higher than that of semolina according to W_b . This result supports the data obtained from moisture sorption isotherms of semolina and farina. Iglesias and Chirife equations indicated good fitness in 0.2–0.6 a_w range, but it is not the others. This might be resulted from semolina and farina is not containing sugar. This equation is available high sugar foods like most dried fruits (Chirife & Iglesias, 1978). The worst fitness to adsorption isotherms of semolina and farina indicated Harkins-Jura equation, this equations is not suitable for semolina and farina. It is reported that Harkins-Jura equation is not very good for most food materials (Chirife & Iglesias, 1978).

Monolayer moisture content (m_0) values, which is an important parameter in food storage and deterioration, obtained by the BET and GAB models are regarded as the sorption capacity of the adsorbent and as the indicator of available of polar sites for bounding of water vapour (Chung & Pfost, 1967a, 1967b). Besides, the monolayer concept is useful because of its relationship with several aspects of the physical and chemical deterioration of dry products (Chirife & Iglesias, 1978).

The monolayer moisture contents with calculated BET and GAB equations at each temperature were found different both products (semolina and farina)

and equations (BET and GAB). Similarity to equilibrium moisture contents, the monolayer moisture contents of semolina and farina were decreased with increasing in temperature calculated by both BET and GAB equations. As shown in Table 3, the m_0 which indicate sorption capacities of the adsorbents were found lower at the higher temperatures. It might be considering that water molecules, state vapour in surrounding of the sample, have higher kinetic energy with higher temperature as expected, the m_0 decreased with increase in temperature. The similar results have been obtained by other investigators (Ertugay, Certel, & Gurses, 2000; Kaymak-Ertekin & Sultanoglu, 2001; Lagoudaki et al., 1993; Menkov, 2000b; Mok & Hettiarachchy, 1990). Also, it is reported that a reduction in the number of polar sites due to chemical and physical changes induced by temperature (McMinn & Magee, 2003). It is might be possible at gelatinization temperature of starch, and coagulation and denaturation temperatures of protein.

In general, the m_0 of semolina was found greater than farina at each temperature accordingly both equations. It is might be reasoned from high protein content of semolina. It was reported that proteins of wheat flour has higher about five times hydration capacity than native starch (Hebrard et al., 2003). The m_0 of foods are change with the composition and operations. In generally for

starchy foods, the m_0 of GAB values that vary from 3.2 to 16.3 g/100 g and for wheat 7.5, bulgur 6.1, HRSW flour 9.97 and Glenlea wheat flour 6.99 g/100 g (Lomauro et al., 1985).

As expected, the m_0 values obtained by the GAB model were higher than those obtained by the BET model. The similar results were obtained by the other investigators (Palou, Lopez-Malo, & Argai, 1997; Wang & Brennan, 1991). The monolayer capacity by BET equation is always less than GAB equation (Timmerman, Chirife, & Iglesias, 2001). Sopade and Ajisegeri (1994) reported that m_0 of BET and GAB equations are not same.

BET and GAB models could be used as an adequate sorption model for sorption data of semolina and farina due to E^0 lower than 10%. The GAB model has an advantage as compared to the BET model since it offers an objective method for drawing sorption isotherms up to $0.9a_w$, while the BET model is limited to $0.2\text{--}0.6a_w$ (Labuza, 1984). Also, reported that the GAB equation has been recommended by European Project Group on COST 90 Physical Properties of Foods (Timmerman et al., 2001).

Constant, C_B , of BET was found higher than C_G of GAB (Table 3). The constants, C_G and C_B , are related energy, but with slightly different physical meanings, and $C_B > C_G$. The BET constant C_B is related logarithmically to the difference between the chemical potential of the sorbate molecules in the pure liquid state and in the first sorption layer. The GAB constant C_G is related to difference of this magnitude in the upper layers and in the monolayer (Timmerman et al., 2001). Interestingly, C_G was found very high at 60°C for both semolina and farina. It is possible that at this temperature the starch was gelatinized and the products were different from initial native starch. Wheat starch is being to gelatinize approximately 57°C (Pomeranz, 1988). Value of k of GAB equation was calculated about 0.7 (Table 3). Also, this could be an indication that adsorption isotherm of semolina and farina was type II and multilayer. If GAB constants calculate $0 < k < 1$ and $C > 2$, sorption isotherm type II (Blahovec, 2004). Constant k of GAB is about 0.7 for starchy foods and is generally lower than 1 (Labuza, 1984; Viollaz & Rovedo, 1999). GAB constant k is a parameter correcting for the properties of the multilayer molecules with respect to bulk liquid (Hebrard et al., 2003). This constant describe the profile of the isotherm at high water activity range, regulating the upswing after the plateau at medium water activity range (Timmerman et al., 2001). It is interesting to note that fitness of GAB at 20°C was not good. Also low k value (0.65) was corrected this state at 20°C.

It was reported that GAB equation a good fit to experimental semolina sorption isotherms, the m_0 value was independent of the particle size and 5.9 g/100 g, and

constants k and C_G , effected particle size, and were 8.3 and 9.5, respectively (Hebrard et al., 2003). Also, Andrieu et al. (1985) reported that m_0 was decreased with increasing temperature for wheat pasta from semolina with calculated BET equation. Desorption of pasta from drum wheat semolina at 40°C, GAB equation constants, m_0 , C_G , and k were determined 5.6, 11.7 and 0.79, respectively (Andrieu et al., 1986).

Lewicki (2000) reported that constants of GAB, m_0 , C and k , were 8.1 g/100 g, 17.4 and 0.74, respectively, for wheat flour. Timmerman et al. (2001) reported that constants of BET, m_0 and C_B , were 7.64 g/100 g and 21.7, and constant of GAB, m_0 , C and k , were 10.24 g/100 g, 18.6 and 0.62 respectively for wheat.

That is considered as indicative of intermolecular attractive forces between adsorption sites and water vapour, the isosteric adsorption heat, as a function of moisture content, shows in Fig. 2. The maximum isosteric heat of adsorption was obtained in the moisture content 6–7% and was higher for semolina (15.2 kJ/mol) than farina (14.34 kJ/mol). To think it beneficial to higher m_0 of semolina than farina. The Q_{st} value sharply decreased with increasing in moisture content to approximately 15% and then was plateau on axis of moisture content. It can be explained considering that the decrease in the adsorption heat with the amount of water adsorbed can be qualitatively explained considering that initially, adsorption occurs on the most polar available sites given rise to the greatest interaction energy. Since these polar sites become occupied, sorption happens on the less polar sites given lower heats of adsorption. After all of polar sites were covered by water, adsorption heat in plateau might be controlled by vapourization heat. Iglesias et al. (1989) were reported that Q_s decreased from 20 to 4 kJ/mol with increasing moisture content from 7 to 14 g/100 g for wheat flour.

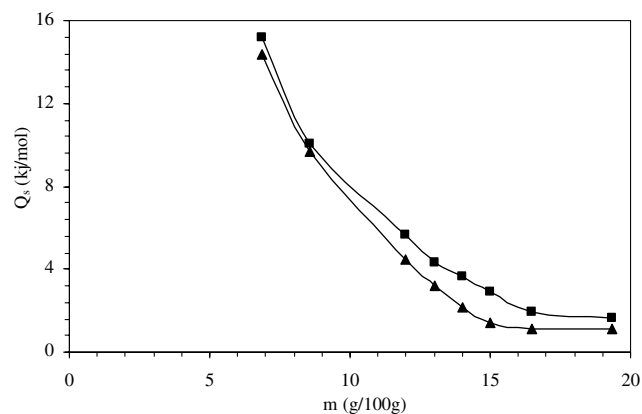


Fig. 2. Isosteric heat of adsorption (Q_s) of semolina (■) and farina (▲) as a function of moisture content (m).

4. Conclusion

The moisture sorption isotherms of semolina and farina were characteristic of the type II isotherm, which is generally referred to as sigmoid isotherms. The sorption isotherm curves indicated that sorption occurred in semolina and farina was multilayer adsorption, and these products were of porous structure and starchy foods. The sorption capacity of farina higher than semolina, it decreased with an increase in temperature at constant water activity because adsorption process is exothermic reaction. Among the sorption models chosen to test, Henderson, Halsey and GAB equations are the most suitable for describing the sorption data well over the range of temperatures of 0.1–0.9 q_w range and $E\%$ lower than 10% water activities investigated except for Harkins-Jura. Regarding the values of the Henderson equation constants, it could be stated that the microporous structure of semolina and farina are more stable. The monolayer moisture content calculated with the GAB equations were higher than BET's both semolina and farina. The maximum adsorption heat were calculated in the moisture content range 6–7% as about 15 kJ/mol. Semolina and farina must be storage below 75% relative humidity at 20°C prevent caking and deterioration because moisture sorption accelerate was increased after 0.75 a_w . The moisture content of the products in this storage conditions could be approximately 12.5%.

Acknowledgement

This research was supported by Akdeniz University Research Found.

References

- Achoba, I. I., Elegbede, J. A., Agbaji, A. S., & Agbaji, E. B. (1991). Moisture isotherms of corn chips at three temperatures. *International Journal of Food Science and Technology*, 26, 547–552.
- Adamson, A. W. (1990). *Physical chemistry of surfaces* (5th ed.). Department of Chemistry, University of Southern California. Los Angeles, A Wiley-Interscience publication, New York.
- Ajibola, O. O., Aviara, N. A., & Ajetumobi, O. E. (2003). Sorption equilibrium and thermodynamic properties of cowpea (*Vigna unguiculata*). *Journal of Food Engineering*, 58, 317–324.
- Andrieu, J., Stamatopoulos, A., & Zafiropoulos, M. (1985). Equation for fitting desorption isotherms of durum wheat pasta. *Journal of Food Technology*, 20, 651–657.
- Andrieu, J., Stamatopoulos, A., & Zafiropoulos, M. (1986). Corn pasta water desorption isotherms. *Lebensmittel-Wissenschaft und Technologie*, 19, 415–418.
- Approved methods of the AACC, (2000) (10th ed.). St Paul, MN: The Association.
- Ayrancı, E., Ayrancı, G., & Doğan, Z. (1990). Moisture sorption isotherms of dried apricot, fig and raisin at 20°C and 36°C. *Journal of Food Science*, 55, 1591–1593.
- Benado, A. L., & Rizvi, S. S. H. (1985). Thermodynamic properties of water on rice as calculated from reversible and irreversible isotherms. *Journal of Food Science*, 50, 101–105.
- Blahovec, J. (2004). Sorption isotherms in materials of biological origin mathematical and physical approach. *Journal of Food Engineering*, 65, 489–495.
- Boki, K., & Ohno, S. (1991). Equilibrium isotherm equations to represent moisture sorption on starch. *Journal of Food Science*, 56, 1106–1108.
- Certel, M. (1990). *Makarnalık (Tr. Durum) ve ekmeklik (Tr. Aestivum) buğdaylardan farklı ısı işlem uygulamalarıyla üretilen bulgur ve ürünlerinin fiziksel, kimyasal ve duyu özellikleri*. PhD thesis, Atatürk University, Faculty of Agriculture, Erzurum.
- Certel, M., & Ertugay, M. F. (1997). The moisture adsorption isotherms of Tarhana. *Turkish Journal of Agriculture Forestry*, 21, 475–479.
- Chen, C. (2003). Moisture sorption isotherms of pea seeds. *Journal of Food Engineering*, 58, 45–51.
- Chirife, J., & Iglesias, H. A. (1978). Equations for fitting water sorption isotherms of foods: Part I: a review. *Journal of Food Technology*, 13, 159–174.
- Chung, D. S., & Pfost, H. B. (1967a). Part I: Heat and free energy changes of adsorption and desorption. *Transactions of the ASAE*, 549–555.
- Chung, D. S., & Pfost, H. B. (1967b). Part II: Development of the general isotherm equation. *Transactions of the ASAE*, 552–554.
- Debnath, S., Hemavathy, J., & Bhat, K. K. (2002). Moisture sorption studies on onion powder. *Food Chemistry*, 78, 479–482.
- Ertugay, M. F. (1996). *Bazı Tahlil Çeşitlerinin Su Aktivitesi, Su Buharı Sorpsiyon İzotermeleri, İzosterik Isıları ve Serbest Enerji Değişimlerine Sıcaklığın Etkisi İle Sorpsiyon Verilerinin Farklı İzoterm Eşitliklerine Uygunluklarının Belirlenmesi*. PhD thesis, Atatürk Üniversitesi, Fen Bilimleri Enstitüsü, Gıda Mühendisliği Anabilim Dalı. Erzurum.
- Ertugay, M. F., & Certel, M. (2000). Moisture sorption isotherms of cereals at different temperatures. *Nahrung*, 44, 107–109.
- Ertugay, M. F., Certel, M., & Gurses, A. (2000). Moisture adsorption isotherms of Tarhana at 25 and 35°C and the investigation of fitness of various isotherm equations to moisture sorption data of Tarhana. *Journal of the Science Food and Agriculture*, 80, 2001–2004.
- Fennema, O. W. (1985). *Food chemistry* (2nd ed., revised and expanded). New York: Marcel Dekker.
- Gal, S. (1975). Recent advances in techniques for the determination of sorption isotherm. In R. B. Duckworth (Ed.), *Water relations of foods*. New York: Academic Press.
- Hebrard, A., Oulahna, D., Galet, L., Cuq, B., Abecassis, J., & Fages, J. (2003). Hydration properties of durum wheat semolina: Influence of particle size and temperature. *Powder Technology*, 130, 211–218.
- Igbeka, J. C., & Blaisdel, J. L. (1982). Moisture isotherms of a processed meat product-Bologna. *Journal of Food Technology*, 17, 37–46.
- Iglesias, H. A., Chirife, J., & Fontan, C. F. (1989). On the temperature dependence of isosteric heats of water sorption in dehydrated foods. *Journal of Food Science*, 54, 1620–1623.
- Inglett, G. E., & Munck, L. (1980). *Cereals for food and beverages. Recent progress in cereal chemistry and technology*. New York: Academic Press.
- İrmik Tebliği, *Turkish Food Codex*, no:2002/21 (2002). Resmi Gazete: 5.03.2002-24686, Ankara.
- Johnson, P. N. T., & Brennan, J. G. (2000). Moisture isotherm characteristics of plantain (*Musa*, AAB). *Journal of Food Engineering*, 44, 79–84.
- Kaymak-Ertekin, F., & Sultanoglu, M. (2001). Moisture sorption isotherm characteristics of peppers. *Journal of Food Engineering*, 47, 225–231.

- Labuza, T. P. (1984). *Moisture sorption: Practical aspects of isotherm measurement and use*. Minneapolis, MN: American Association of Cereal Chemist.
- Lagoudaki, M., Demertzis, P. G., & Kontominas, M. G. (1993). Moisture adsorption behaviour of pasta products. *Lebensmittel-Wissenschaft und Technologie*, 26, 512–516.
- Lomauro, C. J., Bakshi, A. S., & Labuza, T. P. (1985). Evaluation of food moisture sorption isotherm equations. Part I: fruit, vegetable and meat products. *Lebensmittel-Wissenschaft und Technologie*, 18, 111–117.
- Leiras, M. C., & Iglesias, H. A. (1991). Water vapour sorption isotherms of two cake mixes and their components. *International Journal of Food Science*, 26, 91–95.
- Levine, I. N. (1995). *Physical chemistry* (4th ed.). New York: McGraw-Hill.
- Lewicki, P. P. (2000). Raoult's law based food water sorption isotherm. *Journal of Food Engineering*, 43, 31–40.
- Malcolmson, L. J., Matsuo, R. R., & Balshaw, R. (1993). Effects of drying temperature and farina blending on spaghetti quality using response surface methodology. *Cereal Chemistry*, 70, 1–7.
- McMinn, W. A. M., & Magee, T. R. A. (1999). Studies on the effect of the temperature on the moisture sorption characteristic of potatoes. *Journal of Food Process Engineering*, 22, 113–128.
- McMinn, W. A. M., & Magee, T. R. A. (2003). Thermodynamic properties of moisture sorption of potato. *Journal of Food Engineering*, 60, 157–165.
- Menkov, N. D. (2000a). Moisture sorption isotherms of lentil seeds at several temperatures. *Journal of Food Engineering*, 44, 205–211.
- Menkov, N. D. (2000b). Moisture sorption isotherms of chickpea seeds at several temperatures. *Journal of Food Engineering*, 45, 189–194.
- Menkov, N. D., & Gelyazkov, D. I. (2000). Moisture sorption isotherms of the millet seeds. *Czech Journal of Food Science*, 18, 86–90.
- Mok, C., & Dick, J. W. (1991a). Response of starch of different wheat classes to ball milling. *Cereal Chemistry*, 68, 409–412.
- Mok, C., & Dick, J. W. (1991b). Moisture adsorption of damaged wheat starch. *Cereal Chemistry*, 68, 405–409.
- Mok, C., & Hettiarachchy, N. S. (1990). Moisture sorption characteristics of ground sunflower nutmeat and its products. *Journal of Food Science*, 55, 1591–1593.
- Palou, E., Lopez-Malo, A., & Argaz, A. (1997). Effect of temperature on moisture sorption isotherms of some cookies and corn Snacks. *Journal of Food Engineering*, 31, 85–93.
- Pomeranz, Y. (1988). *Wheat: chemistry and technology*. Minnesota, USA: American Association of Cereal Chemists.
- Rouquerol, F., Rouquerol, J., & Sing, K. (1999). *Adsorption by powders and porous solids—Principles methodology and applications*. San Diego, USA: Academic Press.
- Rovedo, O. C., Roberto, J. A., & Constantino, S. (1993). Measuring and modelling the water vapour desorption in sunflower seed. *International Journal of Food Science and Technology*, 28, 153–158.
- Sandoval, A. J., & Barreiro, J. A. (2002). Water sorption isotherms of non-fermented cocoa beans (*Theobroma cacao*). *Journal of Food Engineering*, 51, 119–123.
- Sogi, D. S., Shivhare, U. S., Garg, S. K., & Bawa, A. S. (2003). Water sorption isotherm and drying characteristics of tomato seeds. *Biosystems Engineering*, 84, 297–301.
- Sopade, P. A., & Ajisegeri, E. S. (1994). Moisture sorption study on Nigerian foods maize and sorghum. *Journal of Food Process Engineering*, 17, 33–56.
- Timmerman, E. O., Chirife, J., & Iglesias, H. A. (2001). Water sorption isotherms of foods and foodstuffs: BET or GAB parameters? *Journal of Food Engineering*, 48, 19–31.
- Tsami, E., Marinos-Kouris, D., & Maroulis, Z. B. (1990). Water sorption isotherms of raisins, currants, figs, prunes and apricots. *Journal of Food Science*, 55, 1594–1597.
- Viollaz, P. E., & Rovedo, C. O. (1999). Equilibrium sorption isotherms and thermodynamic properties of starch and gluten. *Journal of Food Engineering*, 40, 287–292.
- Wang, N., & Brennan, J. G. (1991). Moisture sorption isotherm characteristics of potatoes at four temperatures. *Journal of Food Engineering*, 14, 269–282.