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# Sorption equilibrium moisture and isosteric heat of Chinese wheat flours

**X. Han[1,2], X. Wang[1], X.-J. Li[2*] and P. Jiang[2]**

*[1]College of Food Science and Engineering, Jilin University, Changchun 130000, Jilin, China P.R.; [2]Academy of the State Administration of Grains, Bai-wang-zhuang 11, Xi-cheng-qu, Beijing 100037, China P.R.; lixingjun3@yahoo.com*

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**RESEARCH ARTICLE**

## Abstract

Data on equilibrium moisture content (EMC) for six Chinese wheat flour varieties were collected by a gravimetric method at 11-96% equilibrium relative humidity (ERH) and a temperature range of 10-35 °C. Six models were fitted to the sorption data, with the modified Guggenheim Anderson deBoer equation, modified Henderson equation (MHE), and a polynomial equation being the best fits. At a constant ERH, the EMC was negatively correlated with temperature, whereas there was a strong effect of temperature on the sorption isotherms of the wheat flours. Initially, the isosteric heats of adsorption for the wheat flours decreased rapidly with increasing sample moisture content (MC); however, when MC was higher than 15% of the wet basis, further increases in MC caused a slight decrease in heat adsorption values. The heat of vaporisation of the wheat flours approached the latent heat of pure water at a moisture content of ~17.5% wet basis, which was ~2,500 kJ/kg. The isosteric heat of sorption values of the wheat flours predicted by the modified Chung-Pfost equation (MCPE) and MHE model negatively correlated with temperature. At 70% ERH, the safe-storage MC of the wheat flours were 14.71 and 13.88% wet basis at 25 and 35 °C, respectively. Among the six varieties of wheat flours, dumpling flour had significantly higher peak and conclusion temperatures of gelatinisation, and solvent retention capacity (water and lactate) than Gaojin flour, but the latter had a higher peak enthalpy of gelatinisation than dumpling flour. Mixolab pasting analysis at constant hydration further showed that Gaojin four had significantly higher protein weakening and starch setback, but less dough development time and stability time, and lower amylase activity than dumpling flour. These may explain why Gaojin flour has higher moisture sorption isotherms than dumpling flour at the studied temperature range.

**Keywords:** Chinese wheat flours, moisture sorption isotherm, isosteric heat, Mixolab pasting behaviour

## 1. Introduction

Wheat is the third most abundant grain in China with an annual production of 110 million tons. About 88 million tons of wheat flour are annually produced in China. Moisture content is a quality determinant in many food and agricultural products. The transmission of water vapour between a hygroscopic product and the surrounding environment is a physical phenomenon that may have adverse effects on the quality of products during storage, as most food products are vulnerable to spoilage under high-moisture conditions (Deman, 1999; Demczuk and Hoffmann-Ribani, 2012). Food products are usually manufactured in one climatic region and sold in another, with a different water vapour pressure (relative humidity). In this circumstance, water vapour transmission between food products and the surrounding environment occurs at different speeds (Bruin and Berg, 1981). Therefore, wheat flour processors must have adequate knowledge of how to maintain the quality of wheat flour during storage with regard to moisture ingress, and select an appropriate packaging material to prevent adverse effects caused by moisture migration (Cooksey, 2004). However, few reports on the moisture sorption isotherms of Chinese wheat flours exist.

The quality of wheat flours depends mainly on their physical, chemical, and microbiological stability (Erbas *et al.*, 2005; Menkov *et al.*, 2005). This stability results from the relationship between the equilibrium moisture content (EMC) of wheat flours and their corresponding water activity ($a_w$) or equilibrium relative humidity (ERH), at a given temperature. A large number of water vapour adsorption isotherms have been reported for wheat flour (Bushuk and Winkler, 1957; Moreira, *et al.*, 2010; Riganakos and Kontominas, 1997), wheat starch (Mok and Dick, 1991; Taylor *et al.*, 1961), wheat pentosans (Cadden, 1988; Dural and Hines, 1993), wheat gluten (Cherian and Chinachoti, 1996), and whole wheat flour (Martín-Santos *et al.*, 2012). Roman-Gutierrez *et al.* (2002) determined the 25 °C water adsorption isotherms of hard and soft wheat flours at a relative humidity (RH) ranging from 10 to 95%, and described them by Guggenheim-Anderson-deBoer (GAB) models, assuming that no difference exists between the isotherms of the selected hard and soft wheat flours. Erbas *et al.* (2005) determined the moisture adsorption isotherms of semolina (from hard wheat) and farina (from soft wheat) at 20, 35, 50 and 60 °C using the isopiestic method, and indicated that the adsorbed moisture content was significantly affected by product type, temperature and $a_w$. Wang *et al.* (2012) compared the sorption isotherms of high-, middle, and low-gluten wheat flours at 10 to 40 °C and RH from 11 to 87%, but found that the desorption or sorption isotherms were the same for the three kinds of wheat flours. Pollatos *et al.* (2013) determined the moisture sorption isotherms of Greek durum wheat semolina at 25, 30, 35, and 40 °C using the gravimetric (static) and the Novasina hygrometric methods, and found good agreement between sorption isotherms for semolina obtained with the Novasina and the static gravimetric methods. It is imperative to evaluate the allowable moisture content for long-term storage of Chinese wheat flours.

Knowledge of the energy requirement, state, and mode of moisture sorption is important in designing effective wheat flour storage systems. Analysis of food product moisture sorption isotherms by a thermodynamic approach could provide information on energy requirements during dehydration, microstructure, surface physical phenomena, moisture properties, and sorption dynamics (Fasina *et al.*, 1999; Thorpe, 2001). Isosteric heat of sorption ($h_s$), often referred to as differential heat of sorption, is useful in estimating the state of water adsorbed by the solid particles (Fasina *et al.*, 1999), and can be defined as the total energy required to remove a unit mass of water from wheat flours. The level of material moisture content (MC) at which the net $h_s$ approaches the latent heat of vaporisation of free water ($h_v$) is often regarded as an indicator of the amount of 'bound water' in the product (Li, 2012; Öztekin and Soysal, 2000). In recent years, several reports have dealt with the isosteric heat of adsorption of wheat flours (Erbas *et al.*, 2005; Martín-Santos *et al.*, 2012; Moreira *et al.*, 2010; Pollatos *et al.*, 2013), however, only Moreira *et al.* (2010) compared net isosteric heats of desorption and adsorption in wheat flours. The objectives of this study were to collect the adsorptive and desorptive EMC/ERH data for six Chinese wheat flours at 11-96% ERH and a temperature range of 10-35 °C using the gravimetric method, then determine a suitable model for describing their isotherms, and calculate the maximum allowable MC for safe storage and the $h_s$. The overall aim was to provide a guideline for the safe storage, and computer controlling the storage of Chinese wheat flours.

## 2. Materials and methods

### Wheat flour samples and experimental procedures

The six varieties of wheat flours used in this study were noodle flour, gaojin flour, steamed bun flour, snow flour 1, snow flour 2, and dumpling flour. The formerly four flours were collected from food plant one, and the latter two flours from food plant two in July 2015. The two food plants are major food plants in China. They were dehydrated to a MC of 2.56-3.59%, using solid $P_2O_5$ at 35 °C. Rehydrated samples (18.49-19.23%) were also prepared by adding distilled water and equilibrating for 2 weeks in the refrigerator, with shaking once per day.

The EMCs of each variety of wheat flour at five constant temperatures (10, 20, 25, 30, and 35 °C) over an ERH range of 11.3-96.0% were determined by the static gravimetric method, as described in our previous report (Li *et al.*, 2011). Briefly, 27 wide-mouth 250-ml glass bottles, each containing 65 ml of saturated salt solution, were kept in a temperature-controlled cabinet to maintain nine groups of different ERH levels in the specified range. The salt solutions included lithium chloride, potassium acetate, magnesium chloride, potassium carbonate, magnesium nitrate, cupric chloride, sodium chloride, potassium chloride, and potassium nitrate. The measurement at each relative humidity condition was conducted in triplicate. Therefore, a total of 135 bottles were used in an experiment to determine five sorption isotherms for each flour variety. Each sample of wheat flour (~50,000 g) was placed in a small bucket (diameter, 3 cm; height, 4 cm) made of copper wire gauze, and hung on a copper wire pothook under a rubber plug into the wide mouth glass bottle, 2-3 cm above the saturated salt solution. The bottles, with the samples now exposed to the saturated vapor, were kept at a temperature of 35 °C. After 17 days, we began weighing the sample-containing copper wire buckets every other day. The measurements continued until the change in mass between two successive readings became less than 2 mg. The MC of the sample at this constant stage was defined as the EMC and was determined by the oven-drying method (AOAC, 1980). The sample was dried to a constant weight at 103.0±0.5 °C for 3 h. The lower the temperature of exposure, the longer the samples were left to equilibrate. However, the flours exposed to the saturated potassium nitrate and potassium chloride solutions for 3-6 days at higher temperatures were susceptible to fungal growth, and were removed immediately if any mould was visually observed.

### Analysis of the sorption data

The experimental EMC/ERH data were used to construct isotherm curves in Kaleidagraph for Mac 4.1.3v software (Synergy Software, Tokyo, Japan), with ERH and EMC data entered onto the x- and the y-axis, respectively. Six equations were used to fit the EMC data of the wheat flours (Table 1).

Fitting was conducted by non-linear regression analysis in SPSS v13.0 for Windows (SPSS Inc., 2006). The criteria used to determine the best equation for the EMC/ERH data were the determination coefficient ($R^2$), residue sum of squares (*RSS*), standard error (*SE*), and mean relative percentage error (*MRE*). The equations 1-4 were used for calculating $R^2$, *RSS*, *SE*, and *MRE*, respectively:

$$R^2 = 1 - \sum_{i=1}^{n}(m_i - m_{pi})^2 / \sum_{i=1}^{n}(m_i - m_{mi})^2 \quad (1)$$

$$RSS = \sum_{i=1}^{n}(m_i - m_{pi})^2 \quad (2)$$

$$SE = \sqrt{\sum_{i=1}^{n}(m_i - m_{pi})^2 / (n-1)} \quad (3)$$

$$MRE\% = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{m_i - m_{pi}}{m_i}\right| \quad (4)$$

Where, $m_i$ is the experimental value, $m_{pi}$ is the predicted value, $m_{mi}$ is the average of experimental values, and $n$ is the number of observations. The fit of an equation to the EMC/ERH data of wheat flours was considered satisfactory if the *MRE* was lower than 10% (Aguerre *et al.*, 1989).

The differences between the EMC predicted by a given equation and the measured EMC were plotted against measured EMC values to yield residual plots. The residual plots were assessed for patterns or randomness.

### Determination of isosteric heat of sorption of the wheat flours

The $h_s$ for wheat flours was assayed essentially according to our previous report (Li, 2012). Specifically, the $h_s$ is partitioned into two components, the latent heat of vaporisation of free water ($h_v$) and the differential heat of wetting ($h_w$). The $h_s$ to $h_v$ ratio is usually calculated because isosteric refers to a material with the same chemical composition (Thorpe, 2001). The differential heat of sorption for wheat flours was calculated using the equations below.

$$\frac{h_s}{h_v} = 1 + \frac{p_s}{RH} \times \frac{dT}{dP_s} \times \frac{\partial RH}{\partial T}\Big|_M \quad (5)$$

$$h_v = 2501.33 - 2.363 \times t \quad (6)$$

$$P_s = \frac{6 \times 10^{25}}{(273.15+t)^5} \times \exp\left(-\frac{6{,}800}{273.15+t}\right) \quad (7)$$

$$\frac{dP_s}{dT} = \frac{P_s}{273.15+t} \times \left(\frac{6{,}800}{273.15+t} - 5\right) \quad (8)$$

**Table 1. EMC/ERH equations used in this study.**

| Equation name (abbreviation) | Formula[1] | Reference |
|---|---|---|
| Modified Chung Pfost (MCPE) | $\mathrm{ERH} = \exp[-\mathrm{A}\cdot\exp(-\mathrm{C}\cdot\mathrm{EMC})/(\mathrm{B}+t)]$ | Pfost *et al.* (1976) |
| Modified Guggenheim Anderson de Boer (MGAB) | $\mathrm{ERH} = \dfrac{2+\left(\frac{\mathrm{C}}{t}\right)\left(\frac{\mathrm{A}}{\mathrm{EMC}}-1\right) - \left\{\left[2+\left(\frac{\mathrm{C}}{t}\right)\left(\frac{\mathrm{A}}{\mathrm{EMC}}-1\right)\right]^2 - 4(1-\mathrm{C}/t)\right\}^{\frac{1}{2}}}{2\mathrm{B}(1-\mathrm{C}/t)}$ | Jayas and Mazza (1993) |
| Modified Henderson (MHE) | $\mathrm{ERH} = 1-\exp[-\mathrm{A}(t+\mathrm{B})\mathrm{EMC}^{\mathrm{C}}]$ | Thompson *et al.*(1986) |
| Modified Halsey (MHAE) | $\mathrm{ERH} = \exp\left[\dfrac{-\exp(\mathrm{A}+\mathrm{B}t)}{\mathrm{EMC}^{\mathrm{C}}}\right]$ | Pfost *et al.* (1976) |
| Modified Oswin (MOE) | $\mathrm{ERH} = \dfrac{1}{1+[(\mathrm{A}+\mathrm{B}t)/\mathrm{EMC}]^{\mathrm{C}}}$ | Chen and Morey (1989) |
| Polynomial | $\mathrm{EMC} = \mathrm{A}\cdot\mathrm{ERH}^3 + \mathrm{B}\cdot\mathrm{ERH}^2 + \mathrm{C}\cdot\mathrm{ERH} + \mathrm{D}\cdot\mathrm{ERH}^2 t + \mathrm{E}\cdot\mathrm{ERH}\cdot t + \mathrm{F}\cdot t + \mathrm{G}$ | Li and Jiang (2015) |

[1] ERH = equilibrium relative humidity (%); EMC = equilibrium moisture content (% wet basis); t = temperature (°C); A, B, C, D, E, F, and G are the coefficients of equations.

$$\left.\frac{\partial RH}{\partial T}\right|_M = \frac{A \times RH}{(t+B)^2} \times \exp(-C \times M) \tag{9}$$

$$\left.\frac{\partial RH}{\partial T}\right|_M = -\frac{1}{\left\{1+(\frac{A+B\times t}{M})^C\right\}^2}\left\{\frac{B\times C}{M}(\frac{A+B\times t}{M})^{C-1}\right\} \tag{10}$$

$$\left.\frac{\partial RH}{\partial T}\right|_M = A \times M^C \exp\left[-A(t+B)M^C\right] \tag{11}$$

Equation 5 was used to calculate the $h_s$ to $h_v$ ratio from

$dP_s/dT$ and , $\left.\frac{\partial RH}{\partial T}\right|_M$

which could be determined using Equation 8 and 9, respectively. The $h_v$ of free water in Equation 6 was dependent on temperature. The saturated vapour pressure ($P_s$) was calculated using Equation 7.

The depends on $\left.\frac{\partial RH}{\partial T}\right|_M$

the sorption isotherm equation used, and the modified Chung Pfost equation (MCPE) in Equation 9, the modified Oswin equation (MOE) in Equation 10, and the modified Henderson equation (MHE) in Equation 11 were adopted in this study.

### Determination of gelatinisation properties of the wheat flours

The thermal properties of wheat flour with normal MC were determined using a differential scanning calorimeter (DSC) 200F3 (Netzsch, Selb, Germany). Each sample (5.0-5.2 mg) was weighed in an aluminium crucible. Distilled water was added to give a water/sample weight ratio of 2:1. The aluminium crucible was sealed and equilibrated at 4 °C overnight. The DSC temperature was raised from 20-110 °C with a heating rate of 10 °C/min. Each sample was run in triplicate. The data, such as onset temperature ($T_o$), peak temperature ($T_p$), conclusion temperature ($T_c$), and enthalpy of flour gelatinisation, were subjected to analysis of variance and the means were separated by Duncan's multiple range test at $P\leq 0.05$ or $P\leq 0.01$, using the SPSS v13.0 for Windows software (SPSS Inc., 2006).

### Measurement of solvent retention capacity of the wheat flours

The solvent retention capacity (SRC) of wheat flours was determined according the AACC 56-11 approved method (AACC International, 2000) with some modification. One gram (0.001 g) of wheat flour was weighed, and put into a 50-ml round-bottomed capped centrifuge tube, and mixed thoroughly after adding 15 ml distilled water, and centrifuged at 5,000 rpm for 10 min. The supernatant was discarded, whereas the tube was turned upside down on the filter and weighed after drying up. Afterwards, 5% (w/v) sodium carbonate aqueous solution was added and the procedure repeated. Another repeat was performed after adding 5% (w/v) sucrose aqueous solution. A final repeat was performed after the addition of 5% (w/v) lactic acid aqueous solution. The SRC for each stage can by calculated from the equation (12).

$$SRC=\left[\frac{\text{Weight of preciptant} \times (100\%-14\%)}{\text{Wheat flour mass} \times (100\%-\text{MC})}\right]-1 \times 100\% \tag{12}$$

Sodium carbonate SRC relates to damaged starch in wheat flour, lactic acid SRC is related to gluten properties, sucrose SRC is related to pentosans properties, whereas water SRC is influenced by all the components of wheat flour and reflects the integral properties of flours (Guttieri *et al.*, 2004).

### Mixolab measurement

Mixolab is an important instrument used for analysis of thermomechnical properties of wheat dough. The mixing and pasting behaviour of wheat flour dough was measured using a Mixolab (Chopin Technologies, Villeneuve la Garenne, France), as shown by Rosell *et al.* (2007). For an assay at adapted hydration, 45-50 g of wheat flours were placed into the Mixolab bowl, and water required for optimum consistency (1.1 Nm) was added, then the dough weighed at 75 g was evaluated. Both the initial mixing temperature and the water tank temperature were 30 °C. Target torque was 1.1±0.5 Nm. The mixing speed during the entire analysis was 80 rpm/min. The initial mixing was performed at 30 °C and lasted 8 min. Afterwards, temperature was increased to 90 °C within 15 min, at a steady rate of 4 °C/min. After 7 min at 90 °C, the temperature was decreased to 50 °C within 10 min, at a steady rate of 4 °C/min, and then held for 5 min. The total time of the procedure was 45 min. The hydration level of six types of Chinese wheat flours was 60-64%.

For constant hydration assay, the doughs with 60% of water level were evaluated. Parameters of interest, including protein weakness at constant temperature phase ($C_1$-Cs), amylase activity (C3/C4) and starch setback ($C_5$-$C_4$), as well as dough development time (DDT) and stability time (DST) were recorded and /or calculated. Protein weakening (Nm) is the torque difference between the maximum torque ($C_1$) at 30 °C and the torque ($C_s$) at the end of the holding time at 30 °C. Amylase activity or cooking stability is the ratio of the maximum gelatinisation torque ($C_3$) during heating period and a torque ($C_4$) after holding time at 90 °C. Starch setback or gelling (Nm) is the difference between the torque ($C_5$) produced after cooling at 50 °C and the torque ($C_4$) after the heating period.

## 3. Results

### Experimental EMC/ERH data for the wheat flours

The average EMCs of sorption at nine relative humidities ranging from 11.3-96.0% and five temperatures (10, 20, 25, 30, and 35 °C) were obtained for the six varieties of wheat flours and are given in Figure 1. The curves of sorption for all wheat flour samples were sigmoidal in shape. At constant temperature, the EMC increased with an increase in ERH, especially rapidly when ERH was 70%. At constant ERH, EMC decreased with an increase in temperature. There were clear differences between desorption isotherm and adsorption isotherm at the same temperature.

The effect of the wheat flour variety on the 20 °C sorption isotherms is shown in Figure 2. Among the six varieties of wheat flours, Gaojin flour had the highest EMC value, and the EMC values of Dumpling flour were the lowest. However, the EMC data of most of the wheat flour varieties were similar. For the same flour variety, there were clear differences between desorption isotherm and adsorption isotherm at 20 °C.

### Fitting of sorption equations to experimental sorption data

The results of nonlinear regression analyses of fitting the sorption equations of the *M=f(RH,t)* form to the experimental data of wheat flour sorption isotherms are shown in Tables 2 and 3. Statistical parameters used in comparing the equations, such as $R^2$, *RSS*, *SE*, and *MRE*, are given in Table 2 and 3. The residual plot was also evaluated for goodness-of-fit for each equation. The four commonly

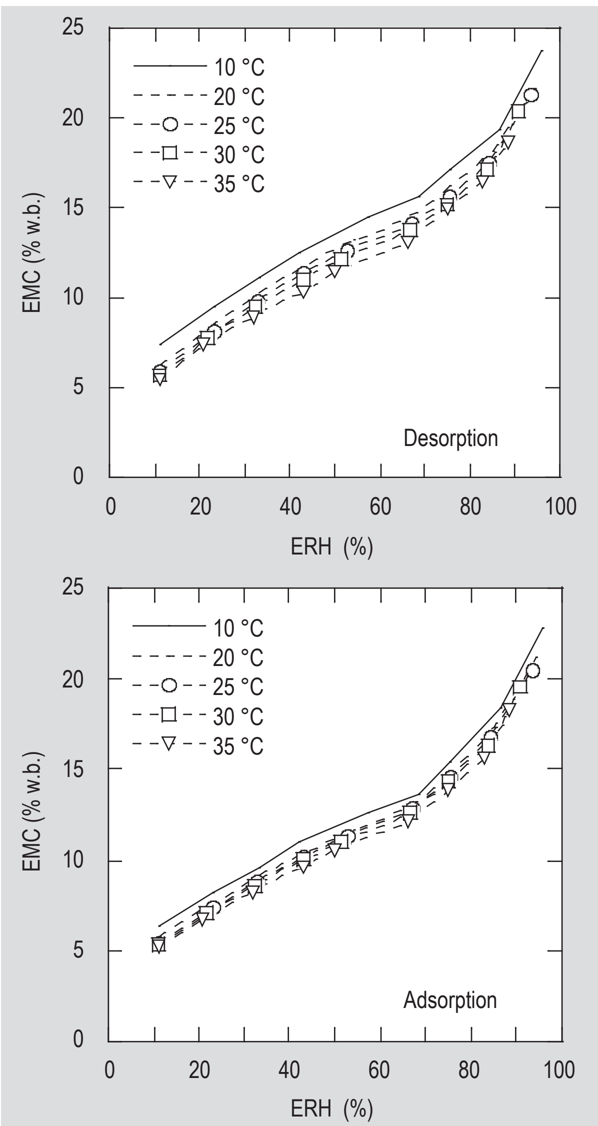


**Figure 1. Influence of temperature on the average sorption isotherms of six varieties of wheat flours.**

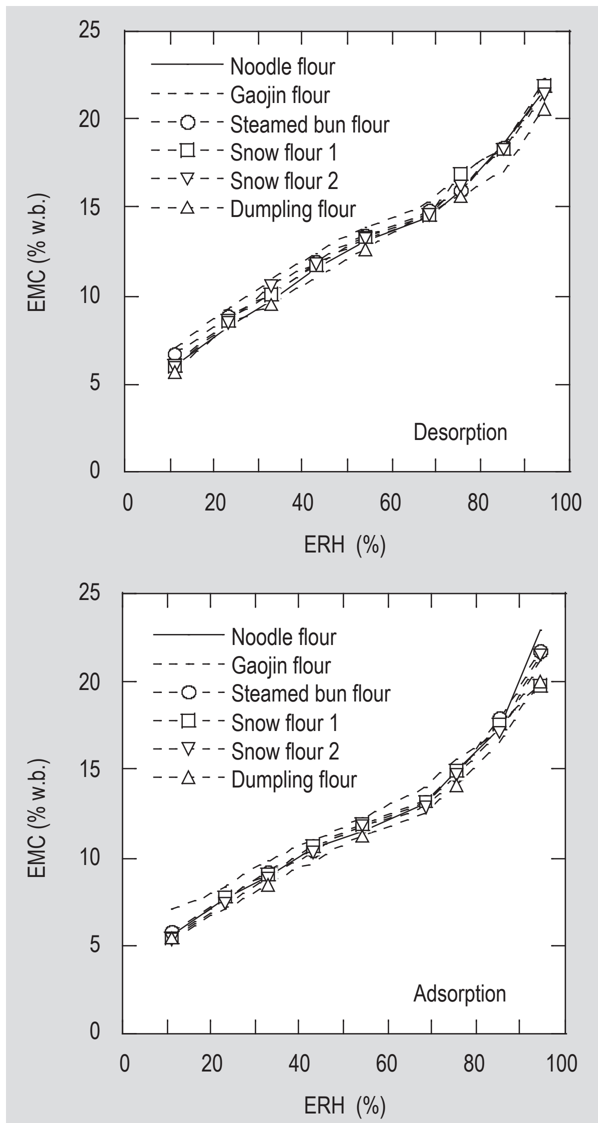


**Figure 2. Influence of varieties on the 20 °C sorption isotherms of Chinese wheat flours.**

**Table 2. The estimation of the coefficients of five commonly used equations in form of *M=f(RH,t)* fitted to the desorption isotherms data of six varieties of wheat flours.**

| Flour variety | Equation | Equation coefficients | | | Statistical parameters | | | | Residual plot |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | $R^2$ | *RSS* | *SE* | *MRE%* | |
| Noodle | MCPE | 618.075 | 37.607 | 0.2335 | 0.9861 | 13.4002 | 3.19E-01 | 3.9186 | Random |
| | MGAB | 9.091 | 0.6159 | 433.536 | 0.9848 | 14.6592 | 3.49E-01 | 3.3571 | Random |
| | MHAE | 8.436 | -1.302E-02 | 3.511 | 0.9268 | 70.8039 | 1.69E+00 | 10.5325 | Patterned |
| | MHE | 1.93E-05 | 53.813 | 2.484 | 0.9907 | 8.9901 | 2.14E-01 | 2.7718 | Random |
| | MOE | 12.695 | -4.985E-02 | 4.253 | 0.9686 | 30.3699 | 7.23E-01 | 6.4285 | Random |
| Gaojin | MCPE | 741.824 | 30.223 | 0.244 | 0.9874 | 11.2977 | 2.69E-01 | 3.5001 | Random |
| | MGAB | 9.787 | 0.5859 | 555.522 | 0.9795 | 18.2871 | 4.35E-01 | 3.5283 | Random |
| | MHAE | 9.533 | -1.637E-02 | 3.822 | 0.9351 | 57.9392 | 1.38E+00 | 8.4529 | Patterned |
| | MHE | 9.64E-06 | 41.645 | 2.757 | 0.9921 | 7.1341 | 1.70E-01 | 2.2627 | Random |
| | MOE | 13.753 | -5.967E-02 | 4.655 | 0.9748 | 22.5017 | 5.36E-01 | 4.9164 | Random |
| Steamed bun | MCPE | 633.123 | 31.195 | 0.2349 | 0.9882 | 11.3538 | 2.70E-01 | 3.5458 | Random |
| | MGAB | 9.469 | 0.6052 | 493.331 | 0.9794 | 19.7345 | 4.70E-01 | 3.3502 | Random |
| | MHAE | 8.936 | -1.543E-02 | 3.6291 | 0.9368 | 60.6534 | 1.44E+00 | 9.3367 | Patterned |
| | MHE | 1.46E-05 | 44.349 | 2.602 | 0.9893 | 10.2698 | 2.45E-01 | 2.7517 | Random |
| | MOE | 13.393 | -5.756E-02 | 4.4109 | 0.9747 | 24.2915 | 5.78E-01 | 5.5873 | Random |
| Snow 1 | MCPE | 727.292 | 40.043 | 0.2349 | 0.9842 | 15.0596 | 3.59E-01 | 4.3216 | Random |
| | MGAB | 9.589 | 0.5978 | 465.743 | 0.9883 | 11.1426 | 2.65E-01 | 3.2058 | Random |
| | MHAE | 8.911 | -1.254E-02 | 3.651 | 0.9219 | 74.5764 | 1.78E+00 | 10.2333 | Patterned |
| | MHE | 1.30E-05 | 55.064 | 2.593 | 0.9938 | 5.8511 | 1.39E-01 | 2.3852 | Random |
| | MOE | 13.124 | -4.786E-02 | 4.425 | 0.9668 | 31.7277 | 7.55E-01 | 6.8306 | Random |
| Snow 2 | MCPE | 794.769 | 56.305 | 0.2387 | 0.9844 | 14.4012 | 3.43E-01 | 4.4887 | Random |
| | MGAB | 9.391 | 0.6034 | 453.283 | 0.9807 | 18.3763 | 4.38E-01 | 3.4317 | Random |
| | MHAE | 8.749 | -1.494E-02 | 3.589 | 0.9317 | 65.0555 | 1.55E+00 | 9.9635 | Patterned |
| | MHE | 1.68E-05 | 44.757 | 2.566 | 0.9892 | 10.2888 | 2.45E-01 | 3.3277 | Random |
| | MOE | 13.078 | -5.492E-02 | 4.356 | 0.9714 | 27.267 | 6.49E-01 | 6.1797 | Random |
| Dumpling | MCPE | 606.755 | 31.401 | 0.2361 | 0.9864 | 12.9642 | 3.09E-01 | 4.3558 | Random |
| | MGAB | 8.736 | 0.6213 | 454.642 | 0.9911 | 8.1607 | 1.94E-01 | 3.2904 | Random |
| | MHAE | 8.186 | -7.901E-03 | 3.499 | 0.9191 | 74.1583 | 1.77E+00 | 10.9106 | Patterned |
| | MHE | 1.63E-05 | 78.578 | 2.466 | 0.9931 | 6.3340 | 1.51E-01 | 2.702 | Random |
| | MOE | 11.943 | -3.177E-02 | 4.233 | 0.9642 | 32.8459 | 7.82E-01 | 6.8422 | Random |

used equations, MCPE (modified Chung-Pfost equation), MHE (modified Henderson equation), MOE (modified Oswin equation), and MGAB (modified Guggenheim-Anderson-deBoer equation), as well as our developed polynomial equation (Table 4), better fit the experimental data of wheat flour sorption isotherms in the range of 11.3-96.0% ERH. MHAE (modified Halsey equation) was worse at fitting the experimental data, displaying a patterned distribution of residual error and higher *MRE* from 6.95-10.92%.

For the form *M=f(RH,t)* and desorption, the equations were ranked in the following order according to accuracy (from highest to lowest): polynomial, MHE, MGAB, MCPE, and MOE. The order for the same form and adsorption was polynomial, MCPE, MHE, MGAB, and MOE. In the case of the *RH=f(M,t)* form, the order for desorption was MHE, MGAB, MCPE, and MOE. For the same form and adsorption, the order was MCPE, MHE, MGAB, and MOE. The polynomial model of the form of *M=f(RH,t)*, and the MCPE, MHE models of the form of *RH=f(M,t)* were considered to better describe the equilibrium moisture data of the six wheat flour varieties in the range of 11.3-96.0% ERH.

Further comparisons of the sorption equations with the form of *M=f(RH,t)* or *RH=f(M,t)* for the six sets of wheat flour isotherm data are given in Table 5. The average values of $R^2$ and error parameters (*RSS*, *SE*, and *MRE*) for the six sets of isotherm data were calculated.

**Table 3. The estimation of the coefficients of five commonly used equations in form of *M=f(RH,t)* fitted to the adsorption isotherms data of six varieties of wheat flours.**

| Flour variety | Equation | Equation coefficients | | | Statistical parameters | | | | Residual plot |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | $R^2$ | *RSS* | *SE* | *MRE%* | |
| Noodle | MCPE | 790.425 | 70.579 | 0.2291 | 0.9954 | 4.4924 | 1.07E-01 | 2.2181 | Random |
| | MGAB | 7.425 | 0.6948 | 703.363 | 0.9863 | 13.4232 | 3.20E-01 | 3.5562 | Random |
| | MHAE | 7.391 | -6.372E-03 | 3.229 | 0.9589 | 40.2749 | 9.59E-01 | 7.8966 | Patterned |
| | MHE | 2.52E-05 | 86.118 | 2.288 | 0.9879 | 11.7535 | 2.80E-01 | 3.3263 | Random |
| | MOE | 11.506 | -2.891E-02 | 3.914 | 0.9874 | 12.3011 | 2.93E-01 | 3.8692 | Random |
| Gaojin | MCPE | 1110.087 | 78.188 | 0.2395 | 0.9952 | 4.2681 | 1.02E-01 | 1.8326 | Random |
| | MGAB | 7.953 | 0.6682 | 933.612 | 0.9874 | 11.2459 | 2.68E-01 | 2.8674 | Random |
| | MHAE | 8.183 | -5.247E-03 | 3.488 | 0.9598 | 35.9524 | 8.56E-01 | 6.9575 | Patterned |
| | MHE | 1.14E-05 | 96.205 | 2.519 | 0.9861 | 12.4911 | 2.97E-01 | 3.2835 | Random |
| | MOE | 12.045 | -2.405E-02 | 4.252 | 0.9876 | 11.0867 | 2.64E-01 | 3.3074 | Random |
| Steamed bun | MCPE | 855.957 | 70.813 | 0.2361 | 0.9941 | 5.433 | 1.29E-01 | 2.368 | Random |
| | MGAB | 7.644 | 0.6767 | 660.914 | 0.9891 | 10.075 | 2.40E-01 | 2.8826 | Random |
| | MHAE | 7.611 | -5.694E-03 | 3.324 | 0.9509 | 45.2768 | 1.08E+00 | 8.5958 | Patterned |
| | MHE | 1.95E-05 | 94.452 | 2.362 | 0.9885 | 10.6408 | 2.53E-01 | 3.1805 | Patterned |
| | MOE | 11.459 | -2.555E-02 | 4.033 | 0.9827 | 15.9868 | 3.81E-01 | 4.6024 | Random |
| Snow 1 | MCPE | 777.818 | 58.225 | 0.2416 | 0.9884 | 10.3359 | 2.46E-01 | 3.3929 | Random |
| | MGAB | 8.027 | 0.6499 | 535.611 | 0.9872 | 11.3894 | 2.71E-01 | 3.3167 | Random |
| | MHAE | 7.881 | -7.919E-03 | 3.417 | 0.9339 | 58.872 | 1.40E+00 | 9.7679 | Patterned |
| | MHE | 2.04E-05 | 76.172 | 2.417 | 0.9905 | 8.418 | 2.00E-01 | 2.5234 | Random |
| | MOE | 11.591 | -3.178E-02 | 4.139 | 0.9725 | 24.5119 | 5.84E-01 | 5.6942 | Random |
| Snow 2 | MCPE | 772.548 | 71.793 | 0.2324 | 0.9939 | 5.7639 | 1.37E-01 | 2.4951 | Random |
| | MGAB | 7.375 | 0.6889 | 592.319 | 0.9873 | 12.11 | 2.88E-01 | 3.4066 | Random |
| | MHAE | 7.232 | -5.638E-03 | 3.207 | 0.9513 | 46.4297 | 1.11E+00 | 9.2416 | Patterned |
| | MHE | 2.65E-05 | 95.095 | 2.262 | 0.9884 | 11.0456 | 2.63E-01 | 3.2938 | Random |
| | MOE | 11.129 | -2.571E-02 | 3.883 | 0.9828 | 16.3908 | 3.90E-01 | 5.0017 | Random |
| Dumpling | MCPE | 720.521 | 67.419 | 0.2429 | 0.9946 | 4.7106 | 1.12E-01 | 2.452 | Random |
| | MGAB | 7.109 | 0.6839 | 532.631 | 0.9901 | 8.6347 | 2.06E-01 | 2.7743 | Random |
| | MHAE | 7.108 | -7.259E-03 | 3.209 | 0.9461 | 46.9946 | 1.12E+00 | 9.6708 | Patterned |
| | MHE | 3.45E-05 | 83.599 | 2.245 | 0.9936 | 5.6096 | 1.34E-01 | 2.6541 | Random |
| | MOE | 10.673 | -2.912E-02 | 3.876 | 0.9808 | 16.722 | 3.98E-01 | 5.3397 | Random |

The better fitted coefficients of equations for average sorption isotherms of wheat flour are summarised in Table 6. These calculated coefficients can be used for describing the process of wheat flour dehydration, and improving physical control of moisture during flour storage.

### Prediction of moisture sorption isotherms by the best fitting equation

The predicted sorption isotherms of wheat flours by different models are displayed in Figure 3 and 4. Temperature had a relatively strong effect on the sorption isotherms of wheat flours predicted by the MGAB and polynomial models at ERH values lower than 60%, whereas above this value, the effect was minor. The MHE model was able to predict the effect of temperature on the sorption isotherms of wheat flours when the ERH was above 30%. The predicted isotherms by the MCPE model distinguished the effect of temperature, and had a higher interval than the one of the MOE model.

The predicted sorption isotherms of the wheat flour varieties at 20 and 30 °C by the polynomial model are displayed in Figure 4 and 5, respectively. Gaojin flour had the highest EMC values, and the EMC values of Dumpling flour were the lowest. However, the EMC data of most of the wheat flours were similar.

Table 7 shows the safe storage MCs of wheat flours at different temperatures and relative humidities. Wheat flour is virtually always stored at an air humidity range of 60-70%. At 60% RH and 25 °C, the absolute safe MC of

**Table 4. The estimation of the coefficients of the polynomial equation fitted to the sorption isotherms data of six varieties of wheat flours.**

| Flour variety | Sorption | Equation coefficients | | | | | | | Statistical parameters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | $R^2$ | *RSS* | *SE* | *MRE%* |
| Noodle | Des[1] | 41.308 | -57.935 | 38.800 | 1.700E-02 | -4.309E-02 | -6.478E-02 | 3.6547 | 0.9941 | 5.7061 | 1.50E-01 | 2.0386 |
| Gaojin | Des | 37.229 | -52.422 | 36.583 | 2.682E-02 | -6.984E-02 | -6.011E-02 | 4.847 | 0.9935 | 5.783 | 1.52E-01 | 2.1466 |
| Steamed bun | Des | 42.505 | -54.895 | 33.964 | -1.817E-01 | 1.789E-01 | -1.189E-01 | 5.491 | 0.9918 | 7.9203 | 2.08E-01 | 2.2816 |
| Snow 1 | Des | 36.375 | -50.766 | 36.063 | -1.647E-02 | -1.256E-02 | -6.536E-02 | 4.228 | 0.9958 | 3.9851 | 1.05E-01 | 1.8899 |
| Snow 2 | Des | 48.669 | -65.387 | 39.006 | -1.763E-01 | 1.759E-01 | -1.163E-01 | 4.5767 | 0.994 | 5.7116 | 1.50E-01 | 2.4256 |
| Dumpling | Des | 33.449 | -48.075 | 35.198 | 8.694E-02 | -9.698E-02 | -4.197E-02 | 3.347 | 0.9951 | 4.5354 | 1.19E-01 | 2.3193 |
| Noodle | Ads | 48.755 | -60.218 | 34.741 | -1.501E-01 | 1.054E-01 | -5.551E-02 | 3.3763 | 0.9952 | 4.7475 | 1.25E-01 | 2.1969 |
| Gaojin | Ads | 43.295 | -54.177 | 31.787 | -7.975E-02 | 7.946E-02 | -6.149E-02 | 4.692 | 0.9938 | 5.535 | 1.46E-01 | 2.0538 |
| Steamed bun | Ads | 45.791 | -57.775 | 33.419 | -1.143E-01 | 1.174E-01 | -7.420E-02 | 3.962 | 0.9956 | 4.047 | 1.07E-01 | 2.2405 |
| Snow 1 | Ads | 40.091 | -54.705 | 36.019 | 2.619E-02 | -5.569E-02 | -3.830E-02 | 3.069 | 0.9941 | 5.2244 | 1.38E-01 | 2.1416 |
| Snow 2 | Ads | 48.998 | -63.671 | 37.083 | -6.504E-02 | 5.339E-02 | -5.778E-02 | 2.9651 | 0.9946 | 5.1199 | 1.35E-01 | 1.8629 |
| Dumpling | Ads | 35.775 | -40.021 | 24.912 | -2.343E-02 | 1.994E-01 | -7.611E-02 | 3.947 | 0.9964 | 3.1401 | 8.26E-02 | 2.0194 |

[1] Des = desorption; Ads = adsorption. All the residual plot is random.

**Table 5. Summary of the results of fitting equations to the six data sets of wheat flour sorption.**

| Model function | Equation | Sorption | Statistical parameters | | | | Order |
|---|---|---|---|---|---|---|---|
| | | | $R^2$ | *RSS* | *SE* | *MRE%* | |
| *M=f(RH,t)* | MCPE | Des[1] | 0.9861 | 13.0795 | 0.3114 | 4.0218 | 4 |
| | MOE | Des | 0.9701 | 28.1673 | 0.6707 | 6.1308 | 5 |
| | MHE | Des | 0.9914 | 8.1447 | 0.1939 | 2.7002 | 2 |
| | MHAE | Des | 0.9286 | 67.1978 | 1.5999 | 9.9049 | 6 |
| | MGAB | Des | 0.9840 | 15.0601 | 0.3586 | 3.3606 | 3 |
| | Polynomial | Des | 0.9941 | 5.6069 | 0.1476 | 2.1836 | 1 |
| | MCPE | Ads | 0.9936 | 5.8339 | 0.1389 | 2.4598 | 2 |
| | MOE | Ads | 0.9823 | 16.1666 | 0.3849 | 4.6358 | 5 |
| | MHE | Ads | 0.9892 | 9.9931 | 0.2379 | 3.0436 | 3 |
| | MHAE | Ads | 0.9502 | 45.6334 | 1.0865 | 8.6884 | 6 |
| | MGAB | Ads | 0.9879 | 11.1464 | 0.2654 | 3.1339 | 4 |
| | Polynomial | Ads | 0.9950 | 4.6357 | 0.1220 | 2.0859 | 1 |
| *RH=f(M,t)* | MCPE | Des | 0.9917 | 2.71E-02 | 6.44E-04 | 6.5125 | 3 |
| | MOE | Des | 0.9897 | 3.36E-02 | 7.97E-04 | 8.2991 | 4 |
| | MHE | Des | 0.9931 | 1.72E-02 | 3.93E-04 | 4.4031 | 1 |
| | MHAE | Des | 0.9630 | 1.20E-01 | 2.87E-03 | 15.6914 | 5 |
| | MGAB | Des | 0.9897 | 3.36E-02 | 8.00E-04 | 5.2397 | 2 |
| | MCPE | Ads | 0.9952 | 1.35E-02 | 3.22E-04 | 3.9553 | 1 |
| | MOE | Ads | 0.9910 | 2.94E-02 | 7.01E-04 | 5.8616 | 4 |
| | MHE | Ads | 0.9942 | 1.89E-02 | 4.52E-04 | 3.9048 | 2 |
| | MHAE | Ads | 0.9736 | 8.59E-02 | 2.05E-03 | 13.2275 | 5 |
| | MGAB | Ads | 0.9925 | 2.43E-02 | 5.78E-04 | 4.5671 | 3 |

[1] Des = desorption; Ads = adsorption. Each statistical parameter is the mean of six data sets.

**Table 6. The better fitting coefficients of five equations for average sorption isotherms of six varieties of wheat flours.**

| Model function | Sorption type | Equation | Equation coefficients | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E | F | G |
| *M=f(RH,t)* | Des[1] | Polynomial | 39.929 | -54.941 | 36.623 | -4.024E-02 | 2.167E-02 | -7.789E-02 | 4.356 |
| | Des | MHE | 1.48E-05 | 51.225 | 2.577 | | | | |
| | Des | MGAB | 9.343 | 0.6048 | 474.554 | | | | |
| | Des | MCPE | 676.167 | 36.582 | 0.2369 | | | | |
| | Des | MOE | 13.000 | -5.033E-02 | 4.388 | | | | |
| | Ads | Polynomial | 43.792 | -55.111 | 33.007 | -1.026E-01 | 8.274E-02 | -6.044E-02 | 3.667 |
| | Ads | MCPE | 826.651 | 69.074 | 0.2368 | | | | |
| | Ads | MHE | 2.18E-05 | 88.041 | 2.348 | | | | |
| | Ads | MGAB | 7.577 | 0.6776 | 646.103 | | | | |
| | Ads | MOE | 11.402 | -2.757E-02 | 4.0147 | | | | |
| | Mean | Polynomial | 41.803 | -54.901 | 34.741 | -7.208E-02 | 5.291E-02 | -6.921E-02 | 4.019 |
| | Mean | MCPE | 729.895 | 49.324 | 0.2369 | | | | |
| | Mean | MHE | 1.84E-05 | 66.141 | 2.463 | | | | |
| | Mean | MGAB | 8.404 | 0.6429 | 546.403 | | | | |
| | Mean | MOE | 12.197 | -3.874E-02 | 4.201 | | | | |
| *RH=f(M,t)* | Des | MHE | 1.50E-05 | 41.255 | 2.631 | | | | |
| | Des | MGAB | 9.654 | 0.5857 | 444.601 | | | | |
| | Des | MCPE | 584.916 | 36.844 | 0.2211 | | | | |
| | Des | MOE | 11.933 | -4.806E-02 | 3.631 | | | | |
| | Ads | MCPE | 783.728 | 67.313 | 0.232 | | | | |
| | Ads | MHE | 1.88E-05 | 74.732 | 2.468 | | | | |
| | Ads | MGAB | 7.913 | 0.6535 | 583.217 | | | | |
| | Ads | MOE | 13.735 | -7.641E-02 | 3.838 | | | | |
| | Mean | MCPE | 658.855 | 48.559 | 0.2264 | | | | |
| | Mean | MHE | 1.74E-05 | 54.067 | 2.548 | | | | |
| | Mean | MGAB | 8.737 | 0.6205 | 504.545 | | | | |
| | Mean | MOE | 12.834 | -6.229E-02 | 3.732 | | | | |

[1] Des = desorption; Ads = adsorption. Each statistical parameter is the mean of six data sets.

tested wheat flours was 13.19%. At 70% RH and 25 °C, the relative safe MC of tested wheat flours was 14.71%.

### Isosteric heat of wheat flour sorption

The $h_s$ was calculated using equations (5-11). The influence of moisture content on the wheat flour $h_s$ values, as determined by the sorption isotherms, is displayed in Figure 6. When the MCPE model was employed, the $h_s$ decreased parabolically and rapidly as the flour MC increased, up to a MC value of 15%. Above 15%, further increases in MC led to smooth decreases in $h_s$. At MC values below 17.5%, $h_s$ negatively correlated with temperature, whereas for a specific temperature, the isosteric heats of desorption were higher than those of adsorption. At a MC of 17.5%, flour $h_s$ values were close to that of pure water.

When the MHE model was employed, Equation 11 was adopted. The isosteric heats of desorption and adsorption of wheat flours at temperatures from 10-35 °C decreased almost linearly as the MC increased. The $h_s$ negatively correlated with temperature, whereas at a specific temperature, the isosteric heat values of wheat flour desorption were higher than those of wheat flour adsorption. As for the MCPE model, it also predicted that the $h_s$ derived from the MHE model is negatively correlated with temperature.

When the MOE model was employed to calculate the wheat flour $h_s$, Equation 10 was adopted. At MC values below 8%, the $h_s$ at 20-35 °C increased rapidly with an increase in flour moisture content. Further increases in MC resulted in $h_s$ decreases, which were rapid in the 8-20% MC but became smooth above 20%. At MC below 15%, temperature had little effect on $h_s$ values. Above MC 15%, $h_s$ appeared to

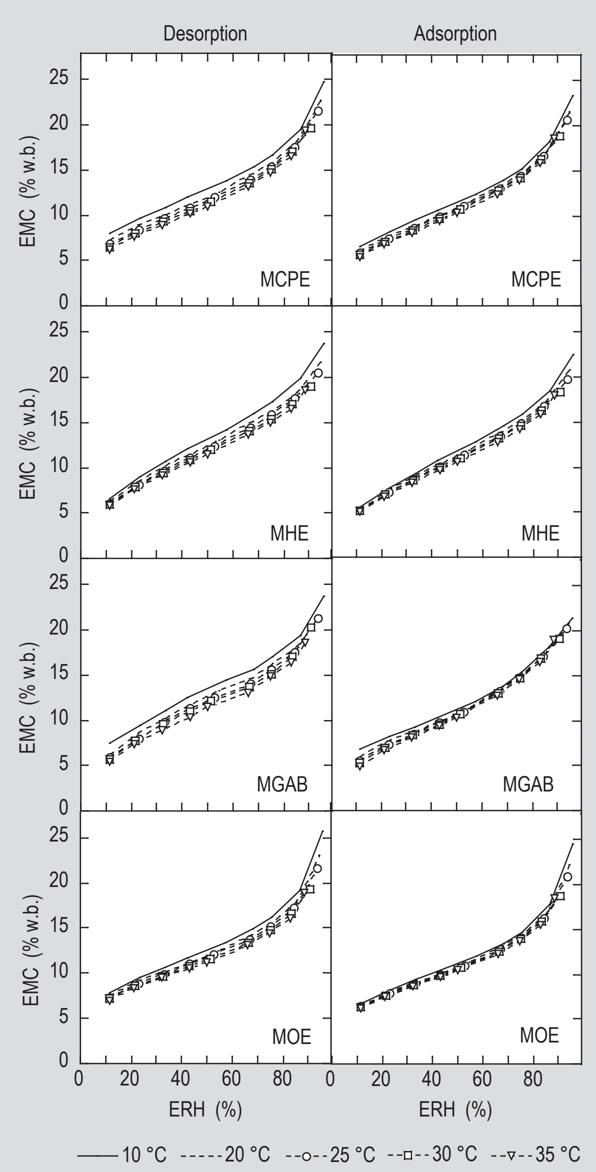


**Figure 3. The predicted moisture sorption isotherms for six varieties of wheat flour by the MCPE, MHE, MGAB, and MOE models.**

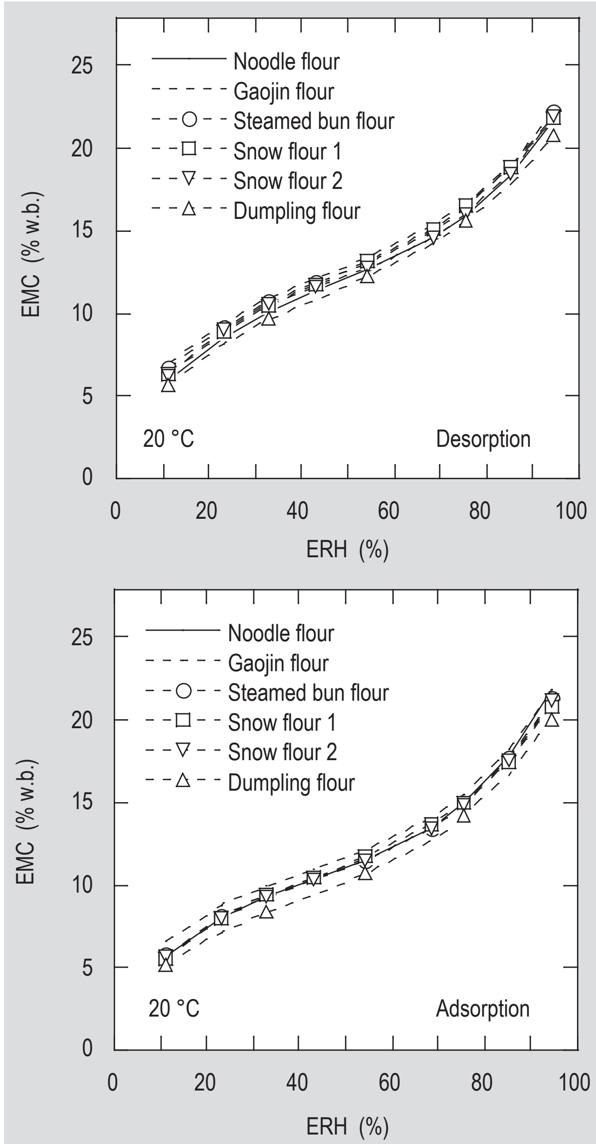


**Figure 4. The predicted moisture sorption isotherms for six varieties of wheat flour by the polynomial model at 20 °C.**

correlate negatively with temperature. At a MC below 8%, the isosteric heat values for wheat flour desorption at a certain temperature were higher than those of wheat flour adsorption, but the opposite was observed above 10% MC.

### Changes in thermal properties of the wheat flours

Table 8 shows the thermal properties of the six varieties of wheat flours. The six varieties had a gelatinisation temperature of 63.1-64.9 °C and an enthalpy of gelatinisation of 4.08-4.96 J/g. Among the six varieties of wheat flours, the two flours that are derived from food plant two, snow flour 2 and Dumpling, had significantly higher $T_p$ and $T_c$ of gelatinisation and lower peak enthalpy of gelatinisation than the other four flours derived from food plant one (Noodle, Gaojin, Steamed bun, and Snow flour 1).

Table 9 shows the SRC of six varieties of wheat flour. Compared to Gaojin flour, Dumpling flour had significantly higher water SRC and lactate SRC, and less sucrose SRC. This indicated that Dumpling flour has more glutens than Gaojin flour.

### Changes in mixolab properties of wheat flours

Mixolab analysis demonstrates dough behaviour of wheat flours during mixing, heating and cooling. Table 10 shows the mixolab pasting properties of the six varieties of wheat flours at constant hydration. The Snow flour2 and Dumpling flour from food plant two had significantly higher

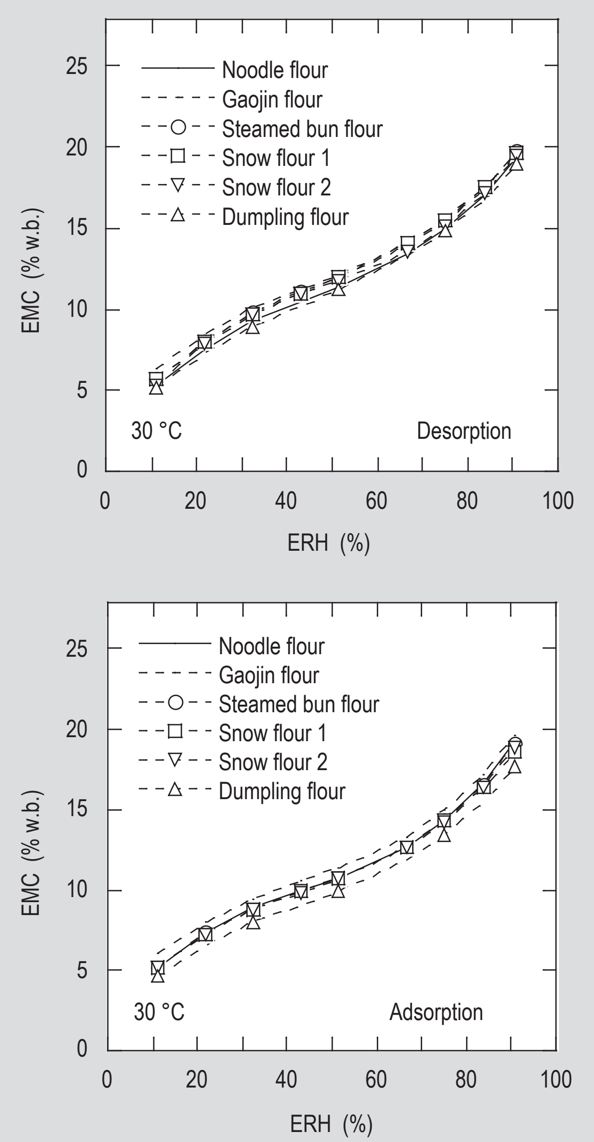


**Figure 5. The predicted moisture sorption isotherms for six varieties of wheat flour by the polynomial model at 30 °C.**

DDT, DST, and amylase activity ($C_3/C_4$), and less protein weakness at constant temperature phase ($C_1$-$C_s$) than the other four types of flour from food plant one (Noodle, Gaojin, Steamed bun, and Snow flour 1). The difference between Snow flour1 and Snow flour2 were DDT, $C_1$-$C_s$, DST, $C_3/C_4$, and starch setback ($C_5$-$C_4$). In comparison with Dumpling flour, Gaojin four had significantly higher protein weakening and starch setback, with less DDT and DST and lower amylase activity.

## 4. Discussion

Roman-Gutierrez *et al.* (2002) reported that the adsorption isotherms of commercial soft and hard wheat flours at 20 °C displayed a classical sigmoidal shape and were adequately described by the GAB equation. In this study, we conclude

**Table 7. The deduced safe storage MC of wheat flour from desorption data by the polynomial model.**

| Flour variety | RH (%) | Storage MC (% w.b.) | | | | |
|---|---|---|---|---|---|---|
| | | 15 °C | 20 °C | 25 °C | 30 °C | 35 °C |
| Noodle | 60 | 13.73 | 13.31 | 12.89 | 12.47 | 12.04 |
| | 70 | 15.30 | 14.86 | 14.43 | 14.00 | 13.56 |
| Gaojin | 60 | 14.58 | 14.12 | 13.66 | 13.20 | 12.73 |
| | 70 | 16.10 | 15.62 | 15.14 | 14.66 | 14.18 |
| Steamed bun | 60 | 14.13 | 13.75 | 13.36 | 12.98 | 12.59 |
| | 70 | 15.71 | 15.29 | 14.88 | 14.47 | 14.05 |
| Snow 1 | 60 | 14.26 | 13.87 | 13.48 | 13.08 | 12.69 |
| | 70 | 15.84 | 15.43 | 15.02 | 14.61 | 14.20 |
| Snow 2 | 60 | 13.84 | 13.47 | 13.10 | 12.73 | 12.36 |
| | 70 | 15.34 | 14.94 | 14.55 | 14.15 | 13.75 |
| Dumpling | 60 | 13.35 | 13.01 | 12.66 | 12.32 | 11.97 |
| | 70 | 14.89 | 14.56 | 14.22 | 13.88 | 13.55 |
| average | 60 | 13.99 | 13.59 | 13.19 | 12.79 | 12.40 |
| | 70 | 15.53 | 15.12 | 14.71 | 14.29 | 13.88 |

that a polynomial model with the form of $M=f(RH,t)$, and the MCPE and MHE equations with the form $RH=f(M,t)$ better describe the equilibrium moisture data of six kinds of Chinese wheat flours in the range of 11.3-96.0% ERH. We also found that temperature had a relatively stronger effect on the sorption isotherms of wheat flours predicted by the MGAB and polynomial models when the ERH was below 60%, but above this value, the effect of temperature was minor. The MHE model was able to show the effect of temperature on the sorption isotherms of wheat flours when the ERH was above 30%. The isotherms predicted by the MCPE model distinguished the effect of temperature and had a larger interval than the one predicted by the MOE model. Although Henderson, Halsey, and GAB models were shown to successfully fit the adsorption isotherms of semolina and farina (Erbas *et al.*, 2005), and of Greek durum wheat semolina (Pollatos *et al.*, 2013), the present study adopted the commonly used models like MCPE, MGAB, MHE, and MOE, as well as our developed polynomial equation, to fit adsorption and desorption isotherms of six kinds of Chinese wheat flours.

The practical implications of moisture sorption hysteresis in cereals and their products can deal with the effect on storage stability (Kapsalis, 1987; Li, 2012). So far our knowledge on elucidation of hysteresis phenomenon of wheat flours moisture sorption is rather limited. The present study shows that wheat flours have clear differences between desorption isotherm and adsorption isotherm at the same temperature. In agreement with these results, the coefficients of MCPE and the isosteric heats for wheat flour desorption and adsorption were different. Sun and Woods (1994) analysed

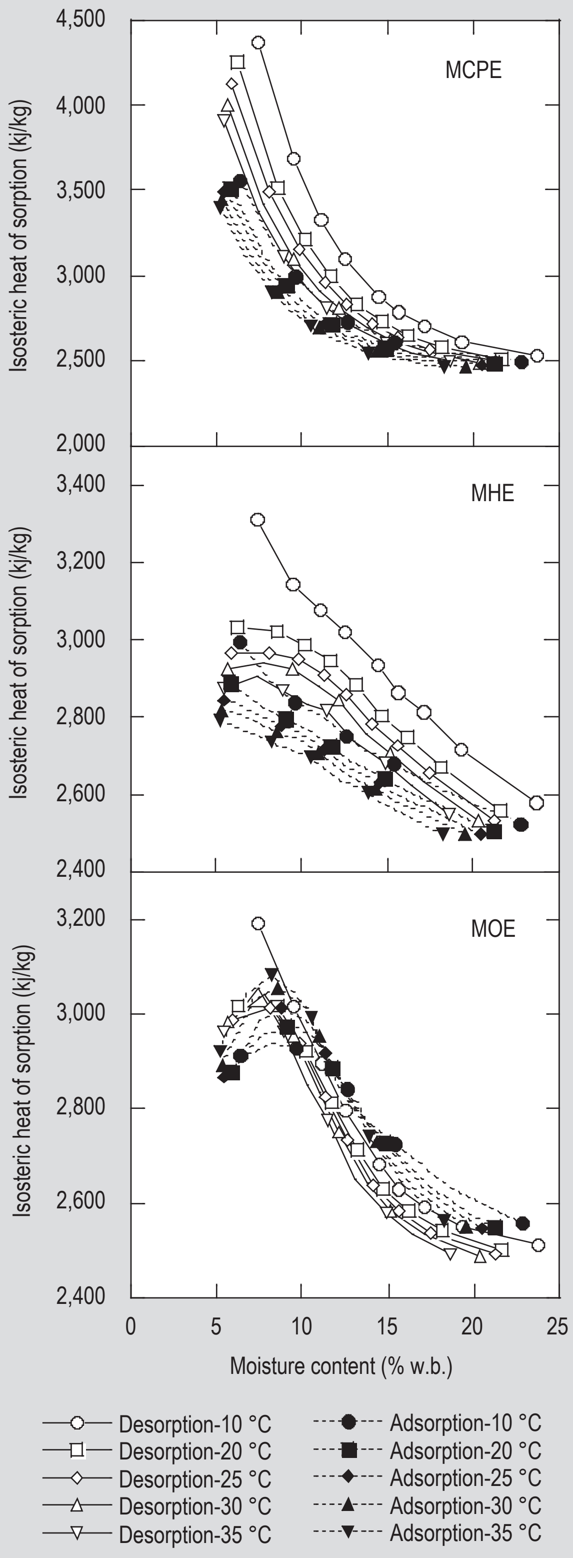


**Figure 6. Comparison of the sorption isoteric heats of wheat flours predicted by differtent models.**

thirty-three source sets of wheat EMC/ERH data with the preferred equations MCPE and MOE, and considered that the wheat hysteresis effect was not greatly influenced by temperature. However, in this study for the average fitted sorption data of six wheat flour varieties, both width and span of the hysteresis effect tended to decrease with an increase in temperature.

Sorption isotherms are extremely important in determining critical moisture, in selecting appropriate packaging material and $a_w$ for acceptability of products that deteriorate mainly by moisture again (Kaymak-Ertekin and Gedik, 2004). The $a_w$ of wheat flour has a strong influence on its quality, process properties, and microbiological stability (Hu *et al.*, 2006). In this study, when the ERH was 60%, the safe storage MC values for Chinese wheat flours at 25 and 35 °C and ERH 60% were 13.19 and 12.40%, respectively. At 70% ERH, the respective MC values were 14.71 and 13.88%. These values are similar to the safe moisture content (below or equal to 14.5%) that is required for wheat flours transported to and from all regions of China (PRC Industry Standard, 1993). We calculated the safe MC of soft and hard wheat flour, using the GAB model that was reported by Roman-Gutierrez *et al.* (2002). When the ERH equals 70%, the MCs of soft and hard wheat flour at 25 °C are 11.3 and 11.6% w.b., respectively. Erbas *et al.* (2005) showed the moisture content of semolina and farina was approximately 12.5% at 20 °C and ERH 75%, and suggested these products must be storage below 75% RH at 20 °C for preventing caking and deterioration due to the increased moisture sorption acceleration after 0.75 $a_w$. We disapprove of the assigned ERH 75% because the ERH, which constitutes the lower limit for most fungi development, is in the region of 65 to 70% (Ayerst, 1969). Our study shows that the maximum allowable moisture content of Chinese wheat flour for safe keeping is 14% w.b. when the environmental temperature ranges from 15 to 35 °C and ERH is 70%. Navaratne (2013) showed that the critical moisture content of wheat noodles, (12% d.b.), was not exceeded even at 85-90% RH, and concluded that wheat noodles had low sensitivity to high atmospheric water vapour concentrations. Moreover, he attributed this hydrophobic phenomenon of wheat noodles to the gluten present in the noodle strings. In our study, however, we observed that the six varieties of wheat flour developed mould 3-6 days after the samples had been exposed to saturated potassium chloride or potassium nitrate solutions at 30-35 °C, i.e. at 85-96% ERH.

Data on isosteric heat values are useful for computational purposes related to the dehydration and storage of Chinese wheat flours. In this study, the $h_s$ for wheat flours analysed by the MCPE model showed rapid increase at moisture contents below 15.0%, and their values were higher than the $h_v$. At MC values over 17.5%, there was no significant difference between the wheat flour $h_s$ and the $h_v$. Similar trends have been reported for the isosteric heat values of

**Table 8. The thermal properties of six varieties of wheat flours.**[1]

| Flour variety | MC (% w.b.) | $T_o$ (°C) | $T_p$ (°C) | $T_c$ (°C) | Peak width (°C) | Peak enthalpy (w/mg) | ∆H (J/g) |
|---|---|---|---|---|---|---|---|
| Noodle flour | 14.2 | 58.8±0.15a | 63.1±0.06d | 68.3±0.06b | 9.5 | 0.1159±0.0032a | 4.96±0.21a |
| Gaojin flour | 13.7 | 58.5±0.45a | 63.3±0.10c | 68.2±0.10b | 9.7 | 0.1068±0.0073a | 4.55±0.28ab |
| Steamed bun flour | 14.3 | 58.7±0.17a | 63.3±0.12c | 68.0±0.40b | 9.3 | 0.1115±0.0066a | 4.53±0.30ab |
| Snow flour 1 | 13.7 | 59.0±0.25a | 63.5±0.10c | 68.4±0.10b | 9.4 | 0.1133±0.0051a | 4.36±0.23b |
| Snow flour 2 | 12.2 | 59.6±0.25a | 64.5±0.25b | 69.8±0.46a | 9.2 | 0.0968±0.0015b | 4.53±0.10b |
| Dumpling flour | 13.8 | 59.8±0.38a | 64.9±0.06a | 70.0±0.49a | 10.2 | 0.0900±0.0053b | 4.08±0.56b |

[1] $T_o$ = onset temperature of gelatinisation; $T_p$ = peak temp.; $T_c$ = conclusion temp.; ∆H = enthalpy of gelatinisation. Data are given as the mean ± standard deviation for triplicate. Values followed by the small letter are not significantly different at *P*≤0.05 according to Duncan's multiple ranges test.

**Table 9. The solvent retention capacity (SRC) of wheat flour.**[1]

| Flour variety | MC (% w.b.) | Water SRC (%) | Sucrose SRC (%) | Lactate SRC (%) | Sodium carbonate SRC (%) |
|---|---|---|---|---|---|
| Noodle flour | 14.2 | 68.09±0.67de | 112.38±2.14c | 121.71±1.27c | 75.82±1.78b |
| Gaojin flour | 13.7 | 73.38±0.62c | 119.01±0.47b | 115.20±4.53d | 79.51±1.21a |
| Steamed bun flour | 14.3 | 67.70±0.19e | 116.78±3.77ab | 116.14±4.74cd | 73.29±0.88b |
| Snow flour 1 | 13.7 | 69.19±0.54d | 106.95±1.75d | 115.02±0.68d | 65.58±2.78c |
| Snow flour 2 | 12.2 | 79.21±1.42a | 120.86±1.01a | 138.73±4.39a | 83.86±5.58a |
| Dumpling flour | 13.8 | 76.90±0.56b | 113.51±0.78c | 132.41±0.71b | 81.81±0.23a |

[1] Data are given as the mean ± standard deviation for triplicate. Values followed by the small letter are not significantly different at *P*≤0.05 according to Duncan's multiple ranges test.

**Table 10. Mixolab pasting properties of wheat flour at constant hydration.**[1,2]

| Flour variety | MC (%) | DDT (min) | $C_1$-$C_s$ (Nm) | DST (min) | $C_3$ (Nm) | $C_3/C_4$ (Nm) | $C_5$-$C_4$ (Nm) |
|---|---|---|---|---|---|---|---|
| Noodle flour | 12.5 | 2.787±0.137c | 0.287±0.027c | 4.511±0.252b | 1.869±0.063ab | 1.009±0.050b | 1.581±0.016a |
| Gaojin flour | 12.0 | 2.252±0.086e | 0.404±0.007b | 3.438±0.099c | 1.910±0.028a | 1.033±0.009b | 1.425±0.165a |
| Steamed bun flour | 12.0 | 3.217±0.042b | 0.324±0.023c | 4.627±0.215b | 1.747±0.045c | 1.042±0.018b | 1.383±0.235ab |
| Snow flour1 | 12.3 | 2.505±0.122d | 0.450±0.023a | 3.397±0.130c | 1.830±0.033b | 1.037±0.005b | 1.513±0.253a |
| Snow flour2 | 13.3 | 5.723±0.261a | 0.081±0.030d | 8.877±0.224a | 1.940±0.079ab | 1.088±0.011a | 1.053±0.166b |
| Dumpling flour | 13.0 | 5.267±0.214a | 0.082±0.018d | 8.573±0.100a | 1.963±0.046a | 1.087±0.001a | 1.153±0.075b |

[1] The assays of mixolab were carried out at constant water level (60% flour basis).
[2] DDT = dough development time (min); $C_1$-$C_s$ = protein weakening (Nm); DST = dough stability time (min); $C_3$ = starch gelatinisation peak torque (Nm); $C_3/C_4$ = amylase activity; $C_5$-$C_4$ = starch setback (Nm). Data are given as the mean ± standard deviation for triplicate. Values followed by the small letter are not significantly different at *P*≤0.05 according to Duncan's multiple ranges test.

melon seeds and cassava (Aviara and Ajibola, 2002), starch powder (Al-Muhtaseb *et al.*, 2004), and Brussels sprouts (Irzyniec and Klimczak, 2003). The steep increase of $h_s$ at low moisture contents indicate that water molecules interact more strongly at lower moisture contents (Martín-Santos *et al.*, 2012; Pollatos *et al.*, 2013). The $h_s$ gradually diminished to the value of the heat of vaporisation of pure water when moisture content reached a maximum value. In the study of Öztekin and Soysal (2000), the $h_s$ of wheat grains approached the $h_v$ at a MC of about 16.7% w.b. Our previous report (Li, 2012) showed this MC to be around 15.0% for wheat grains, close to those of alfalfa pellets (13.8%), gari (13.0%), and winged bean seed (13.0%) (Aviara and Ajibola, 2002; Fasina *et al.*, 1999). In the present study, when the $h_s$ of wheat flours approached the $h_v$, their MC was 17.5% w.b., similar to that of wheat grains.

In the present study, owing to their similar thermal properties, the four varieties of flours from the same plant one (Noodle, Gaojin, Steamed bun, and Snow flour1) had almost superimposable moisture sorption isotherms. The Dumpling flour is characterised by lower sorption isotherms when compared to Gaojin flour, which may be attributed to the significantly higher $T_p$ and $T_c$ of gelatinisation, and the lower peak enthalpy of gelatinisation of the former. Dumpling flour had higher water SRC and lactate SRC than Gaojin flour, but the latter had a higher sucrose SRC than Dumpling. The mixolab pasting analysis at constant hydration further showed that Dumpling flour had higher DDT and DST, and higher amylase activity than Gaojin flour, but Gaojin flour had significantly higher protein weakening and starch setback values. These results may explain Gaojin's higher moisture sorption isotherms compared to that of Dumpling flour at 20-30 °C.

## 5. Conclusions

The curves of moisture sorption for the six wheat flour varieties were sigmoidal. At constant temperature, EMC was positively correlated with ERH, especially at ERH values above 70%. At constant ERH, EMC was negatively correlated with temperature, whereas temperature had a strong effect on the sorption isotherms of wheat flour.

Among the six tested wheat flour varieties, the EMC data for most of them were similar, although Gaojin flour had the highest EMC values, and the EMC values of Dumpling flour were lowest. Among the six varieties, Dumpling flour had significantly higher $T_p$ and $T_c$ of gelatinisation, water SRC, and lactate SRC, as well as higher DDT and DST, and amylase activity than Gaojin flour, but the latter had higher peak enthalpy of gelatinisation and sucrose SRC, and higher values of protein weakening and starch setback than Dumpling flour.

The maximum allowable moisture content of wheat flour for safe keeping is 14% w.b. when environmental temperature ranges from 15 to 35 °C and ERH is 70%. The $h_s$ of wheat flours approached the $h_w$ at a MC of 17.5% w.b. The MCPE and MHE models predicted that the $h_s$ values of Chinese wheat flours negatively correlate with temperature.

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