The specific heat of wheat

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Abstract

Specific heat of Nanduan 1 variety of wheat was determined by Differential Scanning Calorimetry (DSC) in the temperature range of -10 to 110°C and initial moisture content from 19.90% wet basis reduced to 6.23% dry basis by 130°C oven drying. The specific heat ranged from 1.0792 to 5.5336 kJ/kg ºC. A multiple regression model relating specific heat to temperature and moisture content was developed in the temperature range of 0-70°C. The calculated curve fit the observed curve well, with an R-square of 0.99. An equation describing the relationship between density and moisture content was developed. The peak value of the density of wheat was observed in the moisture content range 8% to 10% wet basis.

Keyword: Specific heat, Wheat, Differential Scanning Calorimetry, Physical Properties, Model

1. Introduction

Specific heat is an important property of wheat for analysis of thermal processes because it indicates how much heat is required to change the temperature of a material. It is necessary for the design of drying, storage, aeration and refrigeration systems of grain storage.

Various methods of measuring the specific heat were mentioned by Jayas et al. (1996), and the mixture method was the most common method used for specific heat determination. In addition, differential scanning calorimetry (DSC) was regarded as the most reliable method to measure specific heat of biomaterials, and it is well suited for determining the effect of temperature on specific heat.

Most determinations of specific heat of wheat were carried out by mixture methods. Muir and Viravanichai (1972) used mixture method to study the specific heat of hard red spring wheat. Results showed a linear function of both temperature range -33.5 to 21.8°C and of moisture content in the range 1% to 19% wet basis; however, moisture contents of wheat were obtained by drying at 100ºC or adding weighed amounts of distilled water. ASABE D243.4 (2007) mentioned the specific heats of five kinds of wheat, at a limited range of moisture contents and temperatures, the major factors that affect the specific heat of wheat.

Satoshi (1987) measured the specific heat of 8 species of cereal grains by DSC in the range of about 10 to 70°C, and about 0% to 35% wet basis moisture content. Results suggested a linear relationship between the specific heat and moisture contents, and a quadratic relationship between the specific heat and temperature. However, the moisture contents were adjusted artificially and few other properties of cereal were mentioned.

The major objectives of this study were to determine the specific heat of Nanduan 1 variety of wheat with the moisture content reducing naturally in the temperature range of -10 to 110°C by DSC, to indicate the relationship between the specific heat and the interaction of temperature and moisture content and the relationship between density and moisture content.

2. Materials and methods

2.1. Sample Preparation

Wheat samples (Cultivar: Nanduan 1) used in this test were obtained from a farmer's field in Shandong province in east China during the 2008 harvest season and thoroughly cleaned by hand. Initial moisture content of the wheat sample was 19.90% wet basis. With the moisture content reducing naturally, the moisture content percent wet basis, density and specific heat capacity were determined at the same time. Dry basis wheat samples were obtained by drying samples in a forced draft oven for 19 h at 130°C; all weight loss was considered to be moisture.

2.2. Moisture content

The moisture content of the wheat sample was determined by the oven drying method, oven drying 19 h at 130°C,and all weight loss was considered to be moisture, according to the standardized procedure for moisture content determination by ASABE Standard S352.2 (2007). Three replicated measurements were carried out at each moisture content.

2.3. Density

The density of the wheat bulk (test weight) was determined by filling a one-litre graduated cylinder and weighing the amount of grain according to state standard of China (GB/T: 5498-85). The density of grain kernels (specific gravity) was determined by using a density balance (XS/XP-Ana Density Kit and Mettler xp205) scale graduated to 0.01 mg.

2.4. DSC Procedure

DSC-200PC (NETZSCH Germany) was used to determine the specific heat of Nanduan 1 variety of wheat. After calibrating the equipment for temperature and power, two empty aluminum pans of the same weight were placed in the sample and reference holders respectively. The calorimeter was adjusted to the initial, base-line temperature and allowed to isothermally equilibrate at -20°C, then scanned dynamically at 10ºC per min over the temperature range from -20°C to 120°C for the baseline. A sapphire run then followed: a 0.12 mg sapphire was placed in the sample pan and in the sample holder with an empty pan in the reference holder, and the same procedure was carried out for the standard sample line. The primary samples of wheat were divided into test samples of about 0.12 mg, which was near the weight of the sapphire, and the procedure was repeated for each of the replications of wheat at different moisture contents. The specific heats were calculated by comparison methods in the Netzsch thermal analysis system.

2.5. Statistical analysis

Average and standard error were calculated by PROC MEAN of Statistic Analysis System (SAS), figures were made by Microsoft Excel, the PROC REG procedure of SAS was performed to develop a multiple regression model of the specific heat as a function of temperature and moisture content, and the significance of the regression coefficients was determined at 0.05 levels.

3. Results

3.1. Density

Table 1 shows the moisture content, percent wet basis, and the density of samples of Nanduan 1 variety of wheat used in our studies.

Table 1 Density of samples used for determining specific heat

Moisture content[1] (%), wet basis	Density of kernels[2] (g/cm^3)	Density of grain bulk[1] (g/L)
19.90±0.03	1.3320±0.0027	748.09±0.02
19.41±0.07	1.3291±0.0024	739.00±0.60
18.17±0.04	1.3345±0.0017	759.34±1.08
17.16±0.04	1.3388±0.0016	770.43±0.27
16.77±0.03	1.3404±0.0015	776.87±0.49
15.88±0.01	1.3454±0.0010	783.03±0.20
15.32±0.01	1.3331±0.0071	783.93±0.18
14.60±0.12	1.3410±0.0030	789.80±0.25
14.13±0.09	1.3516±0.0018	794.10±0.50
13.53±0.01	1.3475±0.0047	794.80±0.05
13.45±0.01	1.3553±0.0008	796.95±0.25
12.58±0.11	1.3546±0.0015	796.76±0.20
12.08±0.08	1.3590±0.0009	797.50±0.10
9.95±0.01	/	802.05±0.65
8.17±0.05	1.3822±0.0011	805.00±0.70
6.23±0.01	/	805.03±0.42
0[3]	1.3663±0.0009	/

[1]Average of triplicates; [2]Average of 300 kernels; [3] Dried at 130ºC for 19 hrs; / indicates missing values; Means±SE.

3.1.1. Relationship between moisture content and density of wheat bulk

The relationship between moisture content and density of the wheat bulk is not linear, as shown in Figure 1, so a binomial equation was used to describe the relationship between moisture content and density of the wheat bulk:

$$\rho_b=765.61+9.1664M-0.5189M^2 \quad (1)$$

Where: ρ_b and M are density of bulk and moisture content on a percent wet basis, respectively; R-square is 0.9709, C.V. % is 0.46.

According to equation 1, the peak value of density of the wheat bulk is 806.09 g/L at 8.82% wet basis moisture content. So, the density of the wheat bulk is reduced as moisture content increases at high moisture contents, and it is reversed at low moisture contents.

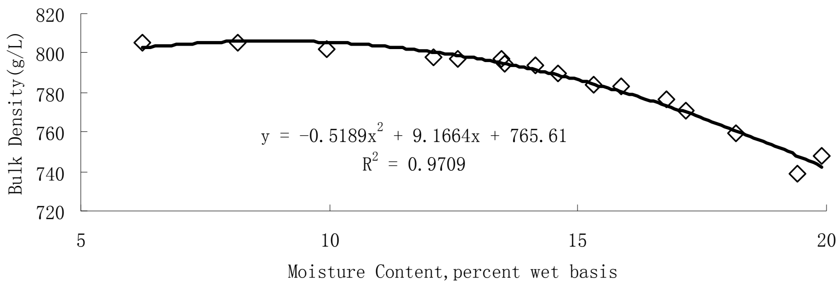

Figure1 Relationship between moisture content and the density of the wheat bulk.

3.1.2. Relationship between moisture content and density of wheat kernels

Figure 2 shows the linear relationship between moisture content and density of wheat kernels:

$$\rho_k=1410.5-4.1695M \quad (2)$$

Where: ρ_k and M are density of kernels and moisture content on a percent wet basis, respectively; R-square is 0.9521, C.V. % is 0.25.

According to equation 2, the dry basis density of kernels should be 1410.5 g/L; however, when the sample was oven dried for 19 hours at 130ºC, the density of kernels was only 1366.3 g/L. These results showed the same trend as the relationship between moisture content and the density of wheat bulk.

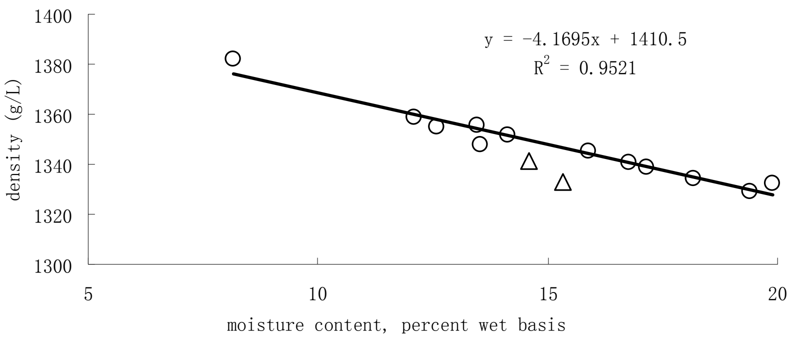

Figure 2 Relationship between moisture content and the density of wheat kernels

3.2. Specific heat

Specific heats of Nanduan 1 variety of wheat at 0.00%, 6.23%, 8.17%, 12.08%, 14.60%, 18.17 and 19.90% wet basis moisture contents were determined using DSC over a temperature range from -10 to 110ºC. The tests were carried out in a randomized order with nine replicates at each moisture content.

3.2.1. Relationship between the specific heat and temperature

The specific heat increased with temperature, but not always linearly, as was observed by other researchers. At low moisture content, the specific heats linearly increased with temperature, however, the specific heats increased at higher temperature more rapidly than at low temperature, and peak values occurred at about 85-90ºC and then were reduced, as shown in Figure 3. We checked the sample weight before and after DSC tests, and the results indicated that the reason for reduction in specific heat was the loss of water in the samples. The average weight loss was 1.10 mg (1.10±0.064 mg, sample weight 12 mg) at 19.90 percent wet basis and 0.33 mg (0.33±0.044 mg) at 8.17 percent wet basis; however, at 0.00 percent wet basis, the weight loss was almost nil. The specific heat could be related to temperature quadratically at the temperature range of 0-70°C, and these equations are shown in Table 2.

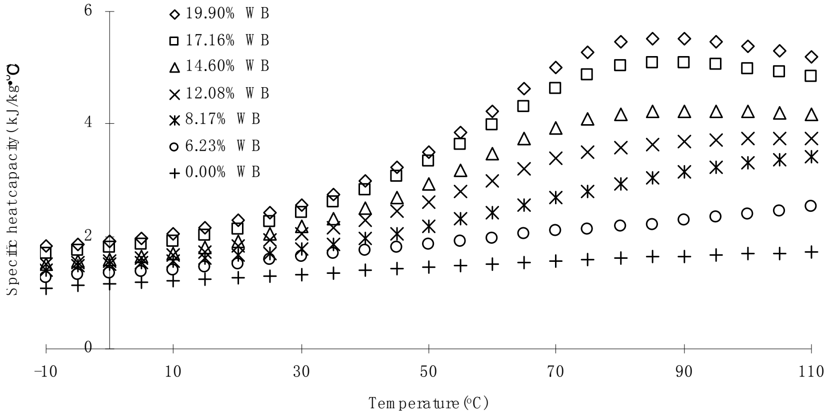

Figure 3 Relationship between the specific heat and temperature

Table 2 Relationship between specific heat and temperature at range of 0-70°C

Moisture content		Quadratic equation*	R-square
Percent wet basis	**Dry basis in decimal**		
19.90	0.2484	c=1.9636+0.0021T+0.0006T^2	0.9992
17.16	0.2071	c=1.8073+0.0054T+0.0005T^2	0.9998
14.60	0.1710	c=1.5964+0.0076T+0.0004T^2	0.9995
12.08	0.1374	c=1.5709+0.0072T+0.0003T^2	0.9998
8.17	0.0890	c=1.5073+0.0033T+0.0002T^2	0.9996
6.23	0.064	c=1.3174+0.01T+0.00002T^2	0.9982
0	0	c=1.1399+0.0058T+0.000006T^2	0.9982

* T=temperature (°C)

3.2.2. Relationship between the specific heat and moisture content

The specific heat data were linearly dependent on the moisture content, and these results were the same as many empirical investigations; therefore, linear regressions were applied as shown in Figure 4. For example:

$$c_{t10} = 1.2031 + 3.3292M \quad (3)$$

$$c_{t30} = 1.3145 + 5.1320M \quad (4)$$

Where c_{t10}, c_{t30} are the specific heat (kJ/kg°C) at 10 and 30ºC, respectively, and M is moisture content in decimal fraction, dry basis.

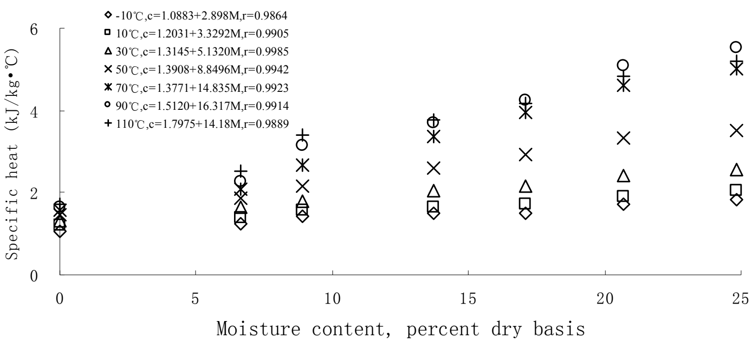

Figure 4 Relationship between the specific heat and moisture content

However, the coefficient of M in the linear equation of Nanduan 1 variety of wheat is affected significantly by the temperature. The relationship could not be simply estimated as the sum of the specific heat of its dry mass and the specific heat of water held in the product at the temperature range of 0-70°C and 4186J/kgºC of water, as described by Jayas et al. (1996) or Young and Whitaker (1973) that plots of specific heat versus moisture content at a constant temperature should have a slope of difference between the specific heat of water and dry mass and pass through the specific heat of water at a wet basis moisture content of 1.0.

3.2.3. Effect of Temperature and Moisture Content on specific heat

Table 3 shows the experimental values of the specific heat of Nanduan 1 variety of wheat every 5 degree at a temperature range of -10 -110^{o}C and at 0.00%, 6.23%, 8.17%, 12.08%, 14.60%, 18.17, and 19.90% wet basis moisture contents, and the specific heat capacity of wheat-nanduan 1 ranged from 1.0792 to 5.5336kJ/kgºC. In general, the specific heats of wheat increased with moisture contents and temperatures in the prescribed moisture content regions and temperature range from 0 to 70ºC.

Table 3 Experimental values of specific heat of wheat kJ/kg^{o}C

Temp. (°C)	M (%WB) 19.90	17.16	14.60	12.08	8.17	6.23	0.00
0	1.9168	1.7903	1.5961	1.5733	1.5145	1.3450	1.1518
5	1.9679	1.8455	1.6410	1.6160	1.5282	1.3746	1.1729
10	2.0475	1.9073	1.7045	1.6626	1.5611	1.4013	1.1981
15	2.1549	2.0172	1.8039	1.7336	1.6024	1.4541	1.2243
20	2.2773	2.1381	1.9169	1.8286	1.6560	1.5113	1.2538
25	2.4128	2.2650	2.0354	1.9278	1.7061	1.5838	1.2815
30	2.5663	2.4184	2.1663	2.0351	1.7787	1.6385	1.3163
35	2.7535	2.5982	2.3207	2.1578	1.8587	1.6926	1.3515
40	2.9761	2.8201	2.4995	2.2911	1.9511	1.7453	1.3872
45	3.2238	3.0667	2.6992	2.4404	2.0581	1.8025	1.4206
50	3.5052	3.3427	2.9296	2.6085	2.1746	1.8573	1.4533
55	3.8401	3.6435	3.1860	2.7950	2.3020	1.9176	1.4866
60	4.2108	3.9708	3.4574	2.9975	2.4289	1.9767	1.5151
65	4.6250	4.3141	3.7314	3.2073	2.5587	2.0341	1.5430
70	4.9967	4.6276	3.9391	3.3773	2.6839	2.0867	1.5673

Average of nine repeats

Based on the analysis of the relationship among the specific heat, temperature and moisture content, respectively, above, the specific heat could be approximately related to temperature quadratically and to moisture content linearly. So a multiple regression model with interaction terms correlating the specific heat to temperature quadratically and moisture content linearly was developed:

$$c=1.11479+3.37138M+0.00913T-0.00028778MT-0.00009249T^2+0.00003354MT^2 \quad (5)$$

Where, C=Specific heat, kJ/kgºC; T=Temperature range from 0 to 70ºC; M=Moisture content, dry basis in decimal, ranging from 0.00% to 19.90% wet basis.

In an analysis using PROC REG of SAS, R-square is 0.9903, root MSE is 0.0819, and C.V.% is 3.6756. Equation 5 can be changed to

$$c=1.11479+0.00913T-0.00009249T^2+(3.37138-0.00028778T+0.00003354T^2)M \quad (6)$$

$$c=1.11479+3.37138M+(0.00913-0.00028778M)T-(0.00009249-0.00003354M)T^2 \quad (7)$$

Equation 6 and 7 indicate that the specific heat linearly increases with moisture content at certain temperatures and quadratically increases with temperature at certain moisture contents, respectively.

4. Discussion

Few reports mentioned, as shown in our studies, that the density of Nanduan 1 variety of wheat decreases with the increase of moisture content at high moisture contents, and that this is reversed at low moisture contents, or that the peak value of density was at the moisture range 8%-10% wet basis. The hardness index, weight and diameter of the sample kernels were tested. The results shown in Table 4 indicated that the average weight loss of kernels was linearly reduced with the decrease of moisture content; however, the average decrease of diameter of kernels was reduced with reduced moisture content (shown in Figure 5). These results confirmed our finding of relationship between densities of wheat and moisture contents.

Table 4 The hardness, weight and diameter of Nanduan 1 variety of wheat

Moisture content Percent wet basis	Hardness index		Weight(mg)		Diameter(mm)	
	Avg.*	S.Dev.	Avg.	S.Dev.	Avg.	S.Dev.
19.90	52.44	16.17	35.32	8.26	3.20	0.55
8.17	69.65	18.12	31.38	7.45	2.98	0.46
0.00	74.82	23.23	28.24	6.62	2.90	0.51

*Average of 300 kernels.

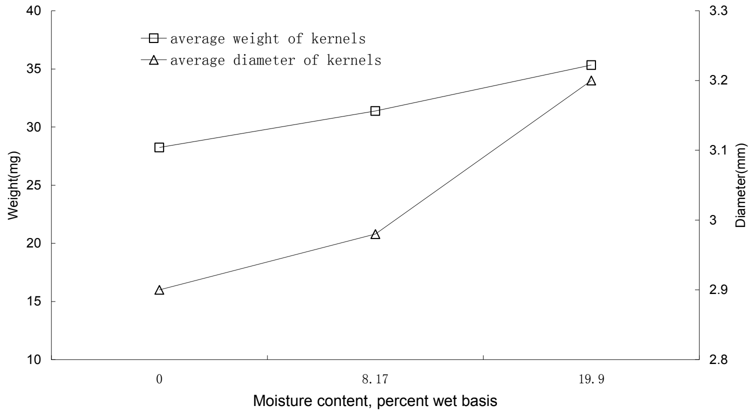

Figure 5 Relationship among moisture content and weight, diameter of kernels

Determination of the specific heats of Nanduan 1 variety of wheat over the temperature range -10-110°C and over the range of moisture content wet basis from zero to 19.90% by the DSC method showed that: 1) The specific heat was linearly dependent on the moisture content at the range of 0-19.9% wet basis; 2) The specific heat could be approximately related to temperature quadratically at the temperature range of 0-70°C moisture loss significantly affected the specific heat tests at high temperatures by DSC; and 3) A multiple regression model with interaction terms correlating the specific heat to temperature quadratically and moisture content linearly was developed at the moisture and temperature range mentioned above with an R-square of 0.99.

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