

Investigation of the Effect of Hot Air Drying of Wheat Gluten on Its Viscoelasticity and Baking Performance by a Systems Analytical Model

F. Meuser,^{1,2} A. Kutschbach,¹ R. Kieffer,³ H. Wieser,³ and P. Schieberle³

ABSTRACT

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Drying experiments were conducted with wet gluten according to a newly developed systems analytical model to describe the effect of drying parameters on the viscoelasticity of wheat gluten and its baking performance. Gluten was extracted from two wheat flours differing in protein, wet gluten content, and viscoelastic properties as determined by extensigrams and farinograms. The glutes extracted from doughs were mixed with wheat starch (A grade) to establish a model system in which the most important drying parameters (hot air temperature, dry matter content of the feed, add-back cycle) could be varied on different levels. The gluten-starch mixtures were dried by a flash dryer. The experiments were designed according to a factorial experimental plan in which the drying parameters were correlated with the shear time of the glutes extracted from the dried products. Aliquots of the extracted glutes were

freeze-dried and used for dough-forming experiments (microfarinograms) and microbaking tests. The dough development time and the baking volume were each statistically related to the shear time. Viscoelasticity of the glutes originating from the two flours decreased with increasing hot air temperature and number of drying steps. Lowering the dry matter content of the feed resulted in a similar reduction. The declining viscoelasticity was reflected in increased dough development time and decreased baking volume. Thus, the functional relationships postulated by the systems analytical model developed for the description of the gluten drying process have been verified on the basis of the statistically evaluated results of the drying experiments. From this follows that the viscoelasticity of gluten can be controlled by varying the parameters of hot air drying processes.

The viscoelastic properties of gluten obtained during the extraction of wheat flours in starch plants are affected when the gluten is dried with hot air in flash dryers. When treated with heat, gluten proteins undergo structural changes that are not well understood (Schofield et al 1983; Kieffer and Belitz 1993; Kieffer et al 1993; Weegels et al 1994; Guerrieri et al 1996). Thermal stressing of gluten and its proteins affects the reconstitution of the viscoelastic properties when the dry gluten is mixed with water and kneaded. Aside from the influence of heat, the nature of the drying process also affects the rheological properties of gluten; the effect of hot-air drying on gluten performance was demonstrated by freeze-drying experiments (Koehler et al 1999). Although the detrimental influence of hot-air drying on gluten performance is well known, the effect of the drying parameters on functional properties of gluten has not yet been investigated systematically. Therefore, we have developed a systems analytical model (Fig. 1) based on the assumption that the product parameters are functionally related to the process parameters, and that the target parameters are similarly related to the product parameters. We have verified the model experimentally to show that the performance of the dried gluten (target parameters such as baking performance) is dependent on gluten properties (product parameters such as shear time), and that these are related to the parameters by which the gluten is treated during drying (process parameters such as hot air temperature).

Wheat gluten obtained by wet milling of wheat flour in wheat starch plants forms compact, viscoelastic lumps. This particular structural characteristic of wheat gluten makes drying very difficult. Before drying, the lumps of wet gluten must be chopped up to increase the surface area and to create the technical and physical conditions required by the drying process, the aim of which is to retain the viscoelastic properties of the wet gluten as far as possible. The toughness of gluten makes it difficult to reduce the lumps of material to particles with a diameter of <1 cm.

Ring dryers are now mainly used for drying gluten, although dryer mills are also used (Grace 1989). Compared with dryer mills

such as the Ultra Rotor (Jaeckering, Hamm, Germany), ring dryers have the advantage of a higher drying capacity. The ring dryers and the dryer mills are both flash dryers. When used for drying gluten, they are fitted with additional attachments to reduce the size of the lumps of wet gluten. The gluten particles thus obtained are mixed with dried gluten to coat the surfaces (Knight 1969), thereby reducing the thermal stressing of the particles passing through the hot air stream of the dryer. Mixing dried gluten with wet gluten evens out the heat transmission through the hot air required to evaporate the water from the coated wet material. The degree to which the gluten is heated is therefore limited to temperatures at which denaturation of proteins can be avoided. There are different technical methods of mechanically mixing and coating the wet gluten with the dry gluten that are integrated in the respective drying systems. The mixed material comes into contact with the hot air at its initial water content. On its way through the dryer, the air very rapidly transfers its heat content to the water evaporated from the particles. The temperature of the drying air thus drops abruptly, and the temperature of the dried material at the dryer outlet is still far lower than that of the outgoing air. Thermal stressing of the wet material is influenced largely by the fact that the particles do not all reach the required final water content in a single add-back cycle due to differences in size. They pass through the dryer repeatedly as partially dried material. The number of add-back cycles required is largely a result of adjusting the solid content of the material to be dried by mixing (coating) the wet material with dry material. The solid content must be set within relatively narrow limits as these are essential for creating a porous particle structure required for water evaporation and heat transmission. The solid content of the mixture is usually adjusted to 60–65%.

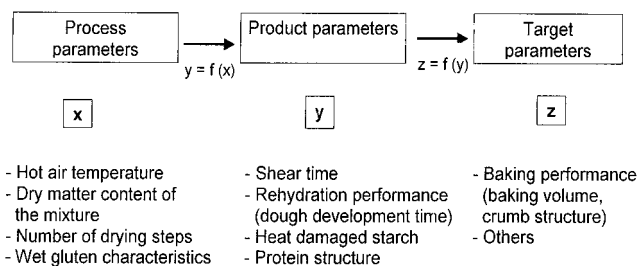


Fig. 1. Systems analytical model of gluten drying experiments.

¹ Technical University Berlin, Institute of Food Technology, Seestr. 11, D-13353 Berlin, Germany.

² Corresponding author. E-mail: meus1533@mailszrz.zrz.tu-berlin.de.

³ German Research Institute of Food Chemistry and Kurt-Hess-Institute of Flour and Protein Research, Lichtenbergstr. 4, D-85748 Garching, Germany.

In memory of Prof. Dr. Hans-Dieter Belitz who had turned seventy this year.

On average, all gluten particles pass through the dryer more than three times due to the mixing ratio required to adjust the solid content. In tests using industrial drying equipment (Ultra Rotor dryer mill), we established that 81% of the particles passed through the dryer more than one time, 35% more than five times, and 10% more than 11 times (Meuser et al 1980).

The gluten drying process shows that changes in viscoelastic properties of the gluten are the result of the temperature of the hot air, the mixing ratio of wet to dry material, and the average number of add-back cycles. Because of the continuous mixing of dry and wet material, it is not possible to observe the relative effects of these influences on the drying results obtained by a dryer operating under industrial conditions in a starch plant. The objective of this work was to conduct and evaluate model drying experiments based on discontinuous mixing, taking into account drying parameters occurring in practice to verify the systems analytical model.

MATERIALS AND METHODS

Experimental Design and Analytical Methods

The experiments were conducted according to the experimental design shown in Table I. Drying experiments were performed using two wheat flours (Type 550, Ellmühle, Koeln-Deutz) differing analytically (Table II). The flours were characterized by standard or laboratory established methods: protein content ICC Standard No. 105/1 1980 ($N \times 5.7$); wet gluten ICC Standard No. 137/1, 1994; extensigram ICC Standard No. 114/1, 1992; farinogram ICC Standard No. 115/1, 1992.

The suitability of the flours for gluten-starch separation was investigated when selecting the flours. Dough development properties affect the degree of separation achieved. In particular, when

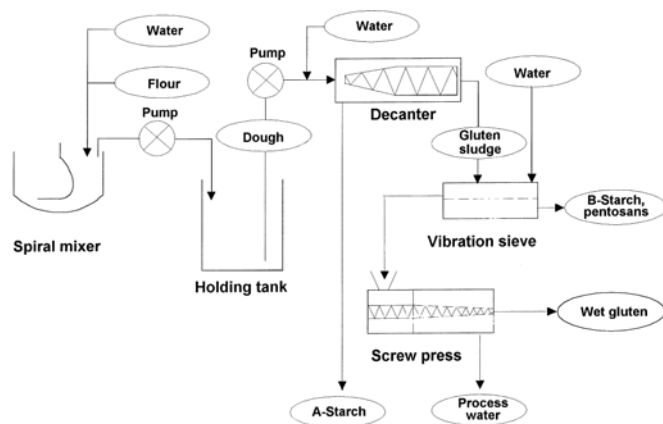


Fig. 2. Diagram of gluten-starch separation equipment.

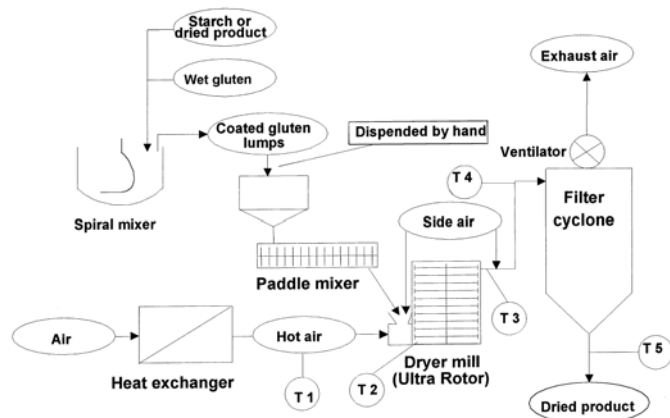


Fig. 3. Diagram of gluten-starch mixing and drying equipment.

using modern centrifugal methods for separation, it is important to agglomerate the gluten to an extent at which a high gluten yield is obtained on processing the flour. Gluten properties specific to both types of wheat selected and the degree of gluten agglomeration are decisive for the degree of viscoelasticity after separation.

Pilot-Scale Gluten Extraction

The gluten-starch separation equipment used for gluten extraction from the wheat flours (A and C) is shown in Fig. 2. For each extraction, 25 kg of flour was mixed with 20–22 kg of water (40°C) in a spiral mixer (Diosna, SP40D type, Osnabrueck, Germany) until the required degree of gluten agglomeration had taken place in ≈ 5 min. The dough was then pumped from the mixer by a screw pump (Netzsch, 2NE20A type, Waldkraiburg, Germany) into a 50-L tank and left for 30 min to allow further gluten development to take place. The dough was then diluted with water (40°C) to a concentration of $\approx 25\%$ dry matter content and pumped into a decanter centrifuge (Westfalia, CA 150 type, Oelde, Germany) using a screw pump at a total throughput of 520 L/hr. Drum and screw speeds of the decanter were 6,000 and 6,030 rpm, respectively. The underflow containing the gluten was washed with water on a vibration sieve (500 μm) (Sweco Separator, 18" type, Nivelles, Belgium). The gluten was transferred manually to a screw press (Vetter, P-Spezial type, Kassel, Germany) and drained. A-type starch, B-type starch, and process water were discarded. The wet gluten was then used in the drying experiments.

Pilot-Scale Drying of Wet Gluten

Wet gluten was mixed with commercial wheat starch (A-type starch, Kroener) or dried product obtained from this mixture in the spiral mixer to adjust the solid content (60 or 65%) as required for the experimental set-up of the drying experiments (Fig. 3). The purpose of the mixing process was to distribute wet gluten in dry material, either in pure starch or dried product consisting of gluten and starch, in the form of gluten strands. The material thus prepared for drying was divided manually into round pieces of ≈ 5 cm diameter and placed into a paddle mixer (Jaeckering, back-coating mixer, Hamm, Germany). Fibrous lumps of the material to be

TABLE I
Experimental Design of Systems Analytical Model

Flour	Drying Step	60% Dry Matter		65% Dry Matter	
		230°C	330°C	230°C	330°C
A	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
C	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x

TABLE II
Analytical Characterization of Flours A and C

Criterion	Flour	
	A	C
Protein (% dm, $N \times 5.7$)	13.3	10.5
Wet gluten (%)	33.2	25.3
Extensigram		
Resistance (BU)	560	330
Extensibility (mm)	146	144
Farinogram		
Water absorption (%)	62.2	60.4
Dough development time (min)	3.5	1.5
Dough stability (min)	8.0	4.5
Shear time of gluten (sec)		
Before freeze-drying ^a	0.8	1.1
After freeze-drying ^b	6.1	6.3

^a Extraction time 20 min.

^b Mixing time 3 min

dried were then reduced to the required elliptical particle shape (2 cm length, 1 cm diameter). The particles were passed through the dryer mill system consisting of a heat exchanger (Jaeckering, T512SH type) and dryer mill (Jaeckering, Ultra Rotor II) in <1 sec and were dried and ground to a powder (particle size 83% smaller than 150 μm). The dried product was then segregated in a filter cyclone (Jaeckering, 16/24 type,) in which the temperature of the dried gluten fell from T4 to T5 (Fig. 3).

An aliquot of the first dried product (first drying step) was again mixed with wet gluten and dried as described above. An aliquot of the second dried product (second drying step) obtained was used to make a third mixture of wet gluten and dried product (third drying step). The solids content of dried mixtures was adjusted to two different levels (60 and 65%, respectively), resulting in six products from each flour for each of two different drying temperatures (230 and 330°C, respectively) (Table I). After the three mixing stages and mixing and adjusting the dry matter content of the material, the average initial dry matter content of the mixture was 60% in a gluten content of 26, 42, and 52%. In the initial dry matter content of the mixture of 65%, the gluten content was 23, 37, and 47%.

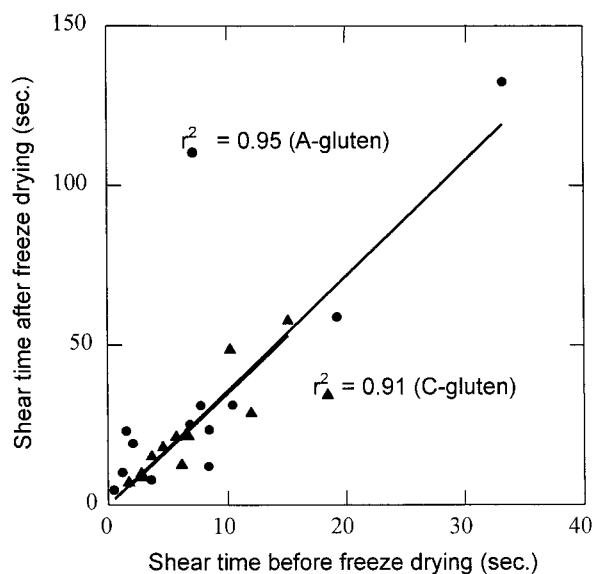


Fig. 4. Correlation between shear time before and after freeze-drying glutens from flours A and C.

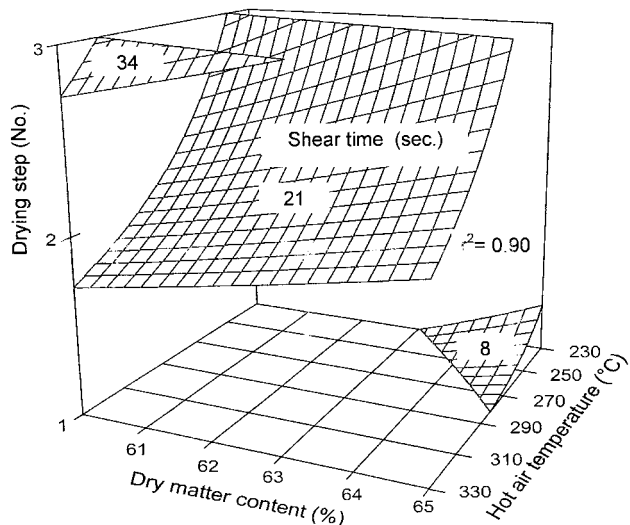


Fig. 5. Influence of flash-drying parameters on shear time of gluten from flour A.

The approach to drying gluten in a mixture of wet gluten and starch or dried product had two major advantages for the assessment of the effect of the drying parameters. The first was that there were defined conditions for determining the thermal stressing of the gluten in the three drying steps. The heat transfer to the material to be dried depends on the difference between the temperature of the hot air and that of the material. However, this temperature did not correspond to the initial temperature of the drying air (T2) as the latter was a combination of the temperature of the hot air stream issuing from the heat exchanger (T1) and that of the side air at the dryer inlet (T3) (Fig. 3). For the sake of simplicity, the hot air temperature was used as a parameter in the model drying tests as the dryer mill setting remained constant, resulting in constant volumetric flows.

The second advantage stemmed from the fact that characterization of the thermal influence by measurement was based on two completely independent variables. In this context, the temperatures >60°C were noted; in this temperature range gluten proteins are denatured and starch begins to swell, provided that the water content of the material is high enough. With regard to the method of measurement, heat stressing of gluten was determined through shear time and heat-damaging of starch.

TABLE III
Shear Time of Commercial Gluten Samples

Sample ^a	Shear Time (sec)	
	Company J	Company K
1	16.5	26.9
2	12.0	24.8
3	12.8	17.9
4	9.1	34.7
5	10.4	14.3
6	14.8	15.2
7	8.6	12.5
8	...	15.7
9	...	18.9
10	...	17.9
Average	12.03	19.85
Standard deviation	± 2.92	± 8.16

^a One sample per day over a period of two weeks.

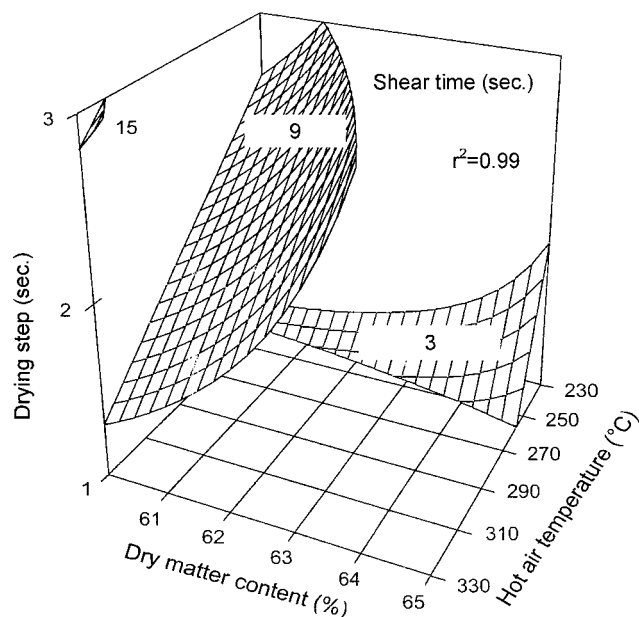


Fig. 6. Influence of flash-drying parameters on shear time of gluten from flour C.

Determination of Heat-Damaged Starch

Dried products were used directly to determine the heat-damaged starch (Klingler 1978). The sample (200 mg) and a formamide sodium sulfate solution (25 mL) were mixed in a volumetric flask (50 mL). The flask was slowly (one motion per second) shaken in a waterbath at 40°C for 10 min. The content was then cooled to 20°C and filtered. The starch extracted from the sample, as well as the total starch content of the sample, was determined by the ICC Standard Method No. 128/1, 1998 (double determination). The ratio of both values $\times 100$ was the heat-damaged starch.

Determination of Shear Time

Viscoelasticity was determined by measuring the shear time of the gluten (Glutograph stress viscometer, Brabender, Duisburg, Germany). The measuring procedure had to ensure that the results of the shear time measurements were comparable for fresh gluten isolated by the centrifugal method (Fig. 2), as well as for gluten extracted from dried products (Fig. 3), which were mixtures of gluten with starch. This involved washing the glutes extracted from the flours and the dried products on gluten washing instruments (10 g doughs) (Glutomatic, Perten Instruments, Stockholm, Sweden) or special purpose laboratory equipment (350 g doughs) (EC 1995) under standardized conditions (ICC 1994) to a protein content ($N \times 6.25$) of $\approx 90\%$ (Meuser 1980). Dried gluten-starch mixtures were rehydrated with water to form a dough to separate gluten from the starch in the gluten washing instruments. These glutes are refined glutes. The shear time of each of the refined glutes was measured immediately afterwards.

For determining the shear time, a piece of refined wet gluten (5 g) was placed in a tube (10 cm long, 4 cm diameter) to which distilled water (10 mL) was added. Four water-topped pieces of one refined gluten were centrifuged in a beaker centrifuge (Labofuge I, Heraeus Christ, Osterode am Harz, Germany) at 4,000 rpm for 9 min. The centrifuged pieces were relaxed, shear time of each piece was determined with the Brabender Glutograph (Sietz 1987), and the average was calculated.

Commercial gluten samples were also treated using this washing process for measurement of shear time. These refined gluten

samples were included in the investigation as an external comparison for the assessment of the drying results. The commercial gluten samples were taken over a period of two weeks from two different processing plants (K and J), one sample per day.

Rheological and Baking Tests

Aliquots of the refined glutes extracted from the wheat flours A and C (Table II) were freeze-dried for use in powdered form in rheological and baking tests to determine the influence of drying on shear time and baking volume. The refined glutes were chopped into small pieces ($< 1 \text{ cm}^3$) and frozen in round bottom flasks (Christ Freeze-Dryer K 40, Osterode am Harz, Germany). The freeze-dried pieces were pulverized in a mortar and pestle to a gritty material and then ground in an impact mill (Ika-Analytical mill, Staufen, Germany) to particle sizes 80% smaller than 150 μm . For determining shear time, freeze-dried material (5 g) was rehydrated with water (10 mL) by mixing the dispersion for 3 min in the Glutomatic to a piece of refined wet gluten. Then the shear time of each refined gluten piece was measured.

Two new micromethods have been developed using a dough system. They are a microfarinogram and a microscale baking test in which dry gluten is incorporated into a recipe for a flour replacement based on commercial corn starch and gelatin. The microfarinograms are made by mixing dried gluten (2.75 g), corn starch (5.5 g) (Mondamin, Maizena), gelatin (0.2 g) (Dr. Oetker), salt (0.2 g), and distilled water (7.8 mL) in a 10-g Brabender Mikrofarinograph at 22°C and 60 rpm (Kieffer and Belitz 1993). The time to achieve maximum resistance is dough development time (DDT). The microscale baking test is a miniaturized version of the rapid mix baking test (Arbeitsgemeinschaft Getreideforschung e.V. 1994). Dried gluten (1.0 g), corn starch (8.0 g), dried yeast (0.25 g) (Dr. Oetker), glucose (0.4 g), DATEM (0.1 g) (Panodan, Danisco), gelatin (0.2 g) dissolved in distilled water (6.8 mL), and salt (0.2 g) are mixed for 1 min at 300 rpm in a cooled beaker at 15°C (mixer MR 300, Braun, Frankfurt a. M., Germany) and processed as described by Kieffer et al (1998). According to this method, the volume of the small loaves is determined by water displacement after coating the surface with paraffin.

TABLE IV
Influence of Drying Parameters on Physical Properties of Wet Gluten and Starch Mixtures^{a,b}

Flour	Drying Step	60% Dry Matter				65% Dry Matter			
		230°C		330°C		230°C		330°C	
		ST	HDS	ST	HDS	ST	HDS	ST	HDS
A	1	1.6	2.6	2.4	2.3	0.9	1.9	1.9	1.9
	2	8.1	12.4	10.8	5.7	3.9	3.6	7.2	3.5
	3	8.8	5.7	33.6	12.4	8.7	6.4	19.6	5.5
C	1	2.8	4.4	6.7	1.3	1.7	1.2	4.6	2.3
	2	5.7	6.3	12.0	3.9	2.8	3.1	6.1	3.7
	3	10.2	9.2	15.1	10.6	3.6	4.3	6.5	10.8

^a ST, shear time before freeze drying (sec); HDS, heat-damaged starch (% of total starch).

^b Bold values indicate outliers for HDS.

TABLE V
Influence of Drying Parameters on Dough Development Time and Baking Performance of Dried Glutes Extracted from Flours A and C^{a,b}

Flour	Drying Step	60% Dry Matter						65% Dry Matter					
		230°C			330°C			230°C			330°C		
		ST-A	DDT	BV	ST-A	DDT	BV	ST-A	DDT	BV	ST-A	DDT	BV
A	1	10.1	3.0	50.1	19.2	3.5	56.9	4.5	2.5	50.3	23.1	3.1	53.2
	2	31.1	6.5	51.3	31.2	6.7	51.0	7.8	3.7	49.0	25.2	5.7	50.6
	3	23.5	6.0	49.0	132.5	13.5	34.4	12.0	6.5	48.8	58.8	8.7	39.0
C	1	9.8	3.0	56.5	21.4	5.0	44.4	6.9	2.7	62.8	18.0	4.5	50.7
	2	21.3	5.2	44.3	28.7	7.5	53.4	8.5	3.7	57.0	12.5	4.3	50.3
	3	48.6	5.0	45.1	57.7	7.5	50.2	15.1	3.5	50.9	22.1	4.5	49.1

^a ST-A, shear time after freeze-drying (sec), DDT, dough development time (min), BV, baking volume (mL).

^b Bold values indicate outliers examined for DDT and BV.

Statistical Evaluation

The results of the tests based on the systems analytical model were evaluated statistically using a regression calculation in accordance with the experimental plan (Table I). Before performing the regression calculation, the measurements were first examined for outliers (Hadi outlier identification method, software SYSTAT v. 6.0, SPSS Inc. Chicago, IL). The correlation between the shear time and freeze drying, between the shear time and the gluten development time, and between the baking volume and both the gluten development time and the shear time was calculated. The probability values of all regression coefficients were $P < 0.05$. The standard deviation of the results for the shear time of the commercial gluten samples was also calculated (Table III).

RESULTS AND DISCUSSION

To understand the results of our work, it must be pointed out that the drying steps were the experimental equivalent to the add-back cycles used in industrial gluten dryers. The drying steps, in contrast to the add-back cycles, were based on a discontinuous drying and remixing procedure. As the dried material was not recirculated during drying, a portion of the material taken from the first drying step was exposed to the same drying conditions three times. The number of drying steps thus simulated recirculation of the material in ring dryers.

The analytical characterization of the flours used in the drying experiments shows that qualitative characteristics of flour A for dough rheology were far superior to those of flour C (Table II). Wet gluten content, corresponding to protein content, resistance to stretching, and dough stability were higher in flour A than in flour C. But the shear times of the glutes extracted from these flours were virtually identical. Freeze-drying increased the shear time of both glutes sixfold. Freeze-drying, which followed separation of the gluten from the starch of the dried products, impaired the viscoelasticity of the extracted gluten, as shown in Tables IV and V, for the shear time before and after freeze-drying of the glutes. There was a very high correlation between the shear time of the glutes from the dried material before and after freeze-drying (Fig. 4). The correlation coefficient was $r^2 = 0.95$ for the gluten from flour A extracted from dried material and $r^2 = 0.91$ for the

gluten from flour C that had also been extracted from the corresponding dried material. This result was of great significance for the determination of the functional correlation between the shear time and the baking volume because the shear time of the glutes before freeze-drying was thus reflected in the shear time after freeze-drying. Establishing this correlation was important for verifying the systems analytical model because the experimental baking tests first required the gluten to be extracted from the dried products by washing and then the gluten was freeze-dried and powdered. Only gluten in powdered form could be incorporated into the recipe used in the microscale baking test.

The shear time measurements of the commercial glutes showed viscoelasticity higher on average (Table III) than that of the gluten obtained from flours A and C (Table IV). It was noticeable that, on average, the shear time for the glutes from plant K were nearly double those of the glutes from plant J. In addition, the values obtained for the glutes from processing plant K fluctuated to a greater extent than those obtained from the glutes from plant J. It was thus assumed that the differences in the shear

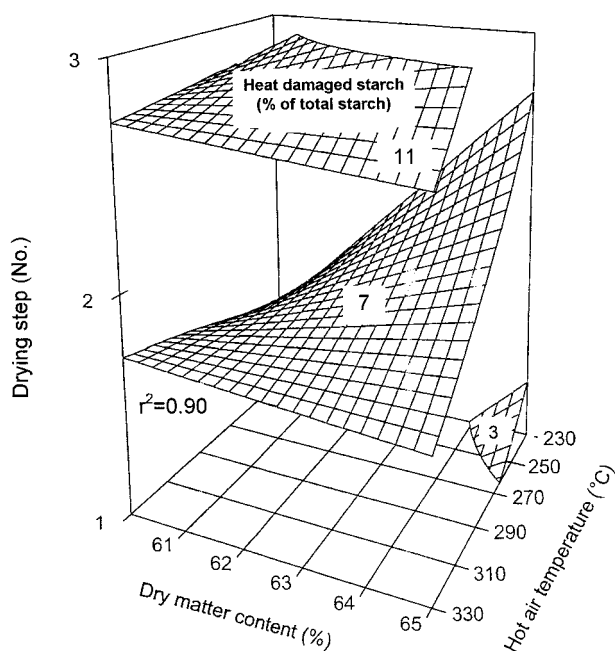


Fig. 7. Influence of flash-drying parameters on heat damage of starch in gluten-starch mixtures of flour C.

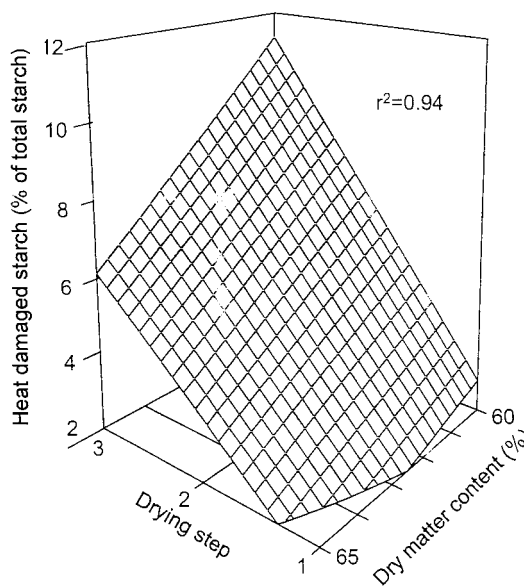


Fig. 8. Influence of flash-drying on heat damage of starch in gluten-starch mixtures of flour A.

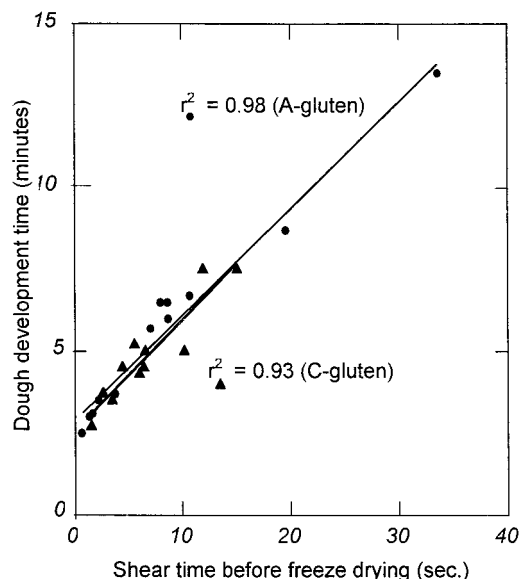


Fig. 9. Correlation between shear time and dough development time of glutes from flours A and C.

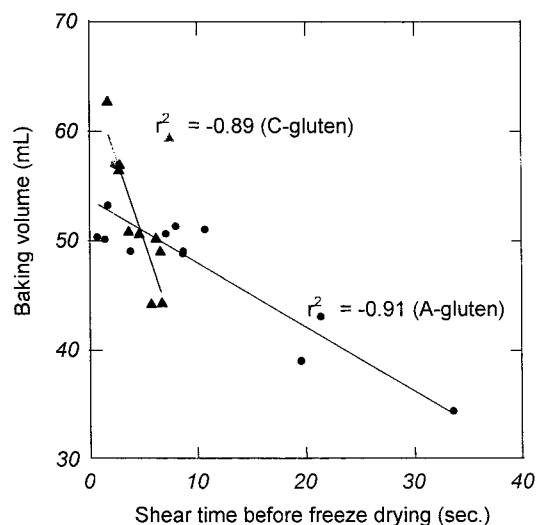


Fig. 10. Correlation between shear time and baking volume of glutes from flours A and C.

time of the glutes from the different plants were dependent on fluctuating running parameters of the dryers in the plants. This assumption was confirmed when the results of the shear time before freeze drying of the glutes obtained in the experimental plan (Table IV) were compared with the shear time of the commercial gluten samples (Table III). The values for the shear time and the heat-damaged starch show that the thermal stressing of the material depended on drying (which increased with each drying step), dry matter content, and drying temperature. The thermal influence due to the drying steps increased at higher drying temperatures and lower dry matter contents.

Differences in the thermal influence on the viscoelasticity of the glutes from each flour were observed. Shear time for the gluten from flour A increased to approximately twice that of the gluten from flour C. The increase depended on the drying parameters as shown in the areas of Figs. 5 and 6 indicating the same shear time in the test space. The validity of the result is confirmed by the high coefficients of determination ($r^2 = 0.90$ for gluten from flour A and $r^2 = 0.99$ for gluten from flour C).

The thermal stressing of the gluten was accompanied by heat damage to the starch in the wet gluten-starch mixture. The degree of heat damage to the starch depended on the drying parameters (Fig. 7) and corresponded to the changes in the viscoelasticity of the gluten measured over the shear time for the dry product obtained from the gluten of flour C. However, the degree of heat damage to the starch could only be determined as a function of the drying step and the dry matter content in drying experiments with the flour from flour A ($r^2 = 0.94$) (Fig. 8). In this case, it would seem that, statistically, the hot air temperature had no influence on the degree of heat damage to the starch. The result can be explained to a certain extent by uneven moistening of the starch when the wet gluten was combined with dry starch owing to the difficulties involved in mixing the tough gluten with the powdered starch. This resulted in a larger deviation in the values of the heat damage to the starch than in the values of the shear time.

The influence of drying parameters on the viscoelasticity of the gluten was determined on the basis of the measured changes in two independent variables. The material being dried was heated to $>60^\circ\text{C}$ in the second and third drying steps. This was indicated principally by the proportion of heat-damaged starch, which increased considerably during these stages. Because the amount of heat-damaged starch leads to conclusions on the solubility of the starch, it may be assumed that the rise in heat-damaged starch was due to a thermally induced increase in starch solubility. However, such an increase only occurs at $>60^\circ\text{C}$. In the $60\text{--}80^\circ\text{C}$ temperature range, it only occurs under thermal drying conditions at nor-

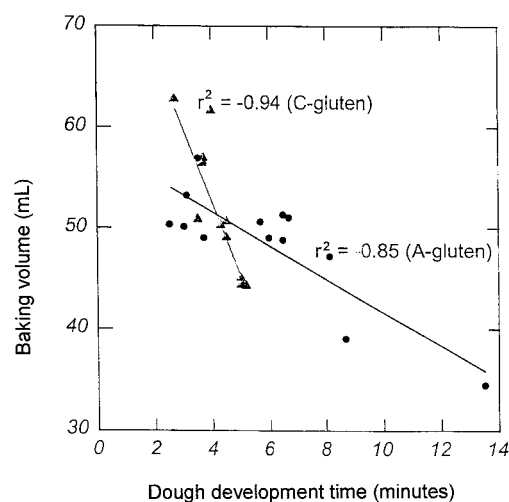


Fig. 11. Correlation between dough development time and baking volume of glutes from flours A and C.

mal pressure if sufficient water is present. This condition was fulfilled in spite of the abrupt evaporation of water occurring during drying under the experimental conditions in the dryer mill.

Further proof of the thermal changes in the gluten as a result of the drying conditions was provided by the microfarinogram. When recording the microfarinograms for the freeze-dried glutes from flours A and C, time elapsed before maximum dough development time (Table V), which corresponds to the maximum dough viscosity, correlated with the shear time of the glutes before freeze-drying (Fig. 9) ($r^2 = 0.98$ and 0.93 , respectively). This correlation is a clear indication that the length of time required for gluten hydration is a function of the thermal stressing. It also indicates a partial denaturation of gluten proteins due to heat transmission under the drying conditions.

The functional correlation between the drying parameters and the product parameters was adequately demonstrated. There is also a functional relationship between the target parameters and the product parameters. This was demonstrated by correlating the baking volume from the microscale baking tests with the shear time of the glutes before freeze-drying. The baking volume achieved in the microscale baking tests was inversely proportional to the shear time (Fig. 10). The result applied to glutes from flours A and C ($r^2 = 0.91$ and 0.89 , respectively). Similar results were obtained when correlating baking volume with dough development time (Fig. 11) because of the high correlation between dough development time and shear time of glutes before freeze-drying ($r^2 = 0.85$ flour A gluten, $r^2 = 0.94$ flour C gluten).

These results show that viscoelasticity, the main quality criterion of gluten, can be controlled over a wide range by varying the hot-air drying parameters of drying processes commonly used in the wheat starch industry. For processing, this implies that the final viscoelastic properties of dried gluten are, by far, more dependent on the drying parameters than on viscoelastic properties of the wet gluten extracted from different flours.

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