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A Model of the Effect of Heated-air Drying on the Bread Baking Quality of Wheat

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A model was developed of the effect of heated-air drying of wheat on bread baking quality for use in computer simulation of wheat drying.

Two varieties of wheat at three initial moisture contents were dried in thin layers with air from 65 to 85°C for periods from 1 min to 4 h to produce both records of the moisture and temperature of the grain during the drying and heat-damaged samples.

The moisture and temperature within the kernels were modelled by fitting a diffusion model to the thin-layer drying curves. Moistures and temperatures of the kernel as a whole were then derived from the distributed parameters so the benefit of using the more complex diffusion model could be assessed. Two models were also used to express the dependence of the rate of loss of loaf volume, relative to controls, on temperature and moisture. The first was a model of zero order with an exponential dependence on temperature and moisture, and the second was a first-order model, using the Arrhenius equation for temperature dependence and a linear equation for moisture dependence.

Both models of loaf volume loss fitted the data equally well when used with the drying model which considered the kernel as a whole. However, the diffusion drying model, in conjunction with the first-order model of loaf volume loss, produced much closer predictions and was concluded to be the best approach.

Published data were used as an independent test. Good results were obtained for runs at and below 80°C air temperature but, at 90 and 100°C air temperature, measured damage was less severe than that predicted by the model probably because of discrepancies between actual kernel temperatures and those predicted by the diffusion model.

1. Introduction

Wheat destined for breadmaking must be sufficiently dry so that it can be stored in ambient conditions without danger of mould growth. Drying is almost always necessary under UK harvest conditions and recent work[1] shows that, if the wheat is to be of the highest quality at harvest, it should be combined earlier and therefore at moistures higher than the 18 to 20% wet basis normally judged appropriate in the main wheat growing regions of the UK. The increased cost of drying can be more than recouped because shedding losses during combining are reduced and final quality is potentially higher. Though near-ambient drying is widely used in the UK, drying with heated air, i.e. at 40°C and upwards, is used for speed, simplicity of management, independence of weather conditions, ability to deal with very moist grain (22% w.b or higher) and for ease of keeping separate, small batches of different variety or quality. However such dryers, if operated with drying air at excessively high temperatures, can damage the quality of wheat for breadmaking.

In selecting wheat for breadmaking, millers use many measures of quality ranging from physical factors, such as fullness of the kernels and cleanliness of the sample, through variety and milling characteristics to such biochemical factors as Hagberg number and

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Notation

- a coefficient in Eqn (4), $°C^{-1}\,s^{-1}$
- b coefficient in Eqn (4), kg dry matter/(kg water s)
- c coefficient in Eqn (7), s^{-1}
- e coefficient in Eqn (7), kg dry matter/(kg water s)
- E activation energy, kJ mol^{-1}
- G wheat viability, %
- k rate constant, s^{-1}
- k_0 value of k at absolute zero, s^{-1}
- M moisture content of grain, kg water/kg dry matter
- M_s moisture content kg/kg, of a shell in the ten-shell model of a grain kernel[16,17]
- n reaction order, dimensionless
- Q quality parameter, dimensions depending on which measure of quality Q represents
- R gas constant, kJ $mol^{-1}\,K^{-1}$
- T temperature, °C
- t time, s
- V loaf volume, cm^3
- V_c volume of control loaf, cm^3
- V_n normalized loaf volume defined by Eqn (6), dimensionless
- V_r loaf volume relative to control, dimensionless
- V_{rs} contribution to loaf volume, relative to control, of a shell in the ten-shell model of a grain kernel[16,17]
- V_u loaf volume of unrisen, i.e. collapsed loaf
- θ absolute temperature of grain, K
- θ_s absolute temperature, K, of a shell in the ten-shell model of a grain kernel[16,17]

microbiological contamination by moulds. It is outside the scope of this paper to go into details and the interested reader is referred to Kent.[2] In heated-air drying of wheat destined for breadmaking, it is the effect of excessively high grain temperature on the wheat protein which concerns us. When flour and water are made into dough certain wheat proteins combine with water to form gluten, an insoluble complex which is toughened by kneading and which, during proving of the dough, traps the gases from fermentation of sugars to form bubbles in the gluten matrix. If such proteins are subjected to sufficiently high temperatures, either in the wheat kernel or as flour, the gluten formed is less elastic and is ruptured by the expanding gases which then escape. The biochemical mechanisms involved in this process are discussed by Booth *et al.*[3] The resulting small, dense and crumbly loaf is unacceptable to consumers. Because loaf volume is an exactly defined, reproducible measure of breadmaking quality which is used internationally in commercial testing, and is a heavily weighted factor in the scoring system used for overall loaf assessment[4] it was used as the primary measure of baking quality in this study.

Heating the kernels during drying is only a means of increasing the drying rate and does not improve the quality in any way, so thermal damage could be avoided by reducing the drying air temperature to ensure that no kernels are heated to the temperatures of 60°C or so at which the onset of damage has been observed.[5] However, if the air temperature in a dryer is raised, the throughput of grain dried over a given moisture range can be increased, and the fuel consumed per unit of water evaporated is reduced.[6] In spite of these operational benefits, operators tend to dry breadmaking wheat at conservative air temperatures because of the reduction in value of the crop if the proteins are damaged.

Although prices vary seasonally, over the years 1983/4–1988/9 in the UK wheat of breadbaking quality has averaged £128·9/t ex farm,[7] and there has been an average difference between it and wheat for animal feeding of £16·9/t. Because yields of baking wheat are lower than feed wheats it is vital to the grower to achieve the milling premium.

Computer simulation, an established method of investigating the design of heated-air grain dryers, in particular their behaviour at steady state,[8,9] is used to investigate aspects of thermodynamic performance and optimization. Simulation of the dynamic state[10] is used to study automatic control of output grain moisture content. Several such simulation models have been reported which predict the physical performance of dryers acceptably well, but none have included a prediction of the loss in baking quality caused by the drying process. Inclusion of a quantitative model for quality loss during drying would allow the upper limits to dryer performance to be defined accurately. This would greatly increase the usefulness of a model for design purposes and more specifically for optimization of drying systems because, without such a constraint, any attempt at optimization simply increases the drying air temperature without limit.

The work reported here was to determine experimentally the effect of grain moisture and temperature during exposed layer drying of wheat on its breadmaking quality, or more specifically loaf volume, and to derive the form of, and coefficients for, a model of baking quality loss during drying in exposed layers.

2. Review of literature

An early approach to the problem of heat damage[11] was to define a minimum acceptable quality, e.g. 95% of control, and then determine the critical temperature, usually expressed as a function of moisture, at which the limiting quality was reached in a time comparable to the length of a typical drying treatment. While the critical temperature approach was useful, it only described the onset of significant damage and not the rate at which damage occurred and therefore could not be applied to conditions of changing temperature and moisture.

Becker and Sallans,[12] using a more analytical approach, described the rate of loss of loaf volume by a first order process,

$$-\frac{dV_r}{dt} = V_r k \tag{1}$$

They expressed the rate constant, k, as a function of temperature using an Arrhenius equation

$$k = k_0 \exp\left[-E/(R\theta)\right] \tag{2}$$

The work of Becker and Sallans is important because Eqn (1) can be integrated to compute loss of loaf volume under the varying temperature and moisture conditions of drying, as shown by Nellist.[13] However, Eqn (1) in which $V_r \rightarrow 0$ as $t \rightarrow \infty$ can only be valid for small amounts of heat damage because in practice the asymptotic value of V_r is not zero; even a completely "collapsed" loaf has a volume of 35 to 55% of a control loaf so the minimum value which V_r can reach lies between 0·35 and 0·55.

These studies all used grains or samples of flour sealed in some closed container, the outer surfaces of which were held at a constant elevated temperature. The temperature of the samples would have risen at different rates depending on the overall heat transfer coefficient and this leads to uncertainties about effective exposure times. In addition, the moisture gradients which develop during diffusion-controlled drying of wheat kernels would have been absent so the situation is not truly representative of drying processes.

Nellist,[14] used both sealed heating and drying and showed that loss of seed viability, which is a function of seed moisture and temperature, could be calculated during drying to predict the viability of the dried grain. His approach was to determine the rates of viability loss at conditions of constant temperature and moisture, and then to integrate through the changing grain moisture and temperature during drying to calculate the cumulative damage. Loss of viability has been found to relate closely to loss of baking quality,[15] so all samples in the present study were also tested for viability. Further studies[16,17] of heat and mass transfer during single layer drying have improved the accuracy of grain moisture and temperature prediction. These results can be used to improve simulation of deep bed drying and thereby enable better predictions of quality loss to be made.

More recently, Wassermann *et al.*[18] reported a set of treatments in which wheat was dried at constant air conditions rather than heated at constant moisture as Becker and Sallans[12] did. Treatment time ranged from 2 to 1,000 min, air temperatures from 50 to 100°C and initial moisture contents from 15·5 to 21·8% wet basis. Though very few details are given[19] the authors seem to have used two dryers. One dried a 100 g sample in an exposed layer where the sample was weighed to monitor drying rate, and thermocouples were implanted in several kernels to sense their temperature. The second dryer used a 5 kg sample which was subsequently tested for quality, but the authors do not indicate whether the drying rates or temperature histories of the two samples differed. Quality tests included germination and baking of test loaves.

Using multiple linear regression, the authors determined the coefficients of a general reaction rate model, reported by Schreiber *et al.*[20]

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = kQ^{n} \tag{3}$$

From their data for germination, wet gluten content and test loaf volume, they determined that the reactions were of order zero, i.e. n in Eqn (3) was not significantly different from zero. The reaction rate was assumed to be an exponential function of seed moisture and temperature,

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = k_0 \exp{(aT + bM)} \tag{4}$$

Values of a, b and k_0 were calculated by Schreiber *et al.*[20] for germination, wet gluten content and relative specific loaf volume, defined as the ratio of specific volume of the test loaf, cm^3/g, to that of the control. The form of the equation is not ideal except for small reductions in the value of Q because Q is not asymptotic to a finite positive value, as required for a loaf volume model, or to zero, as required for a model of germination or wet gluten content. Also, because Eqn (4) predicts a linear rate of loss of quality with time at given values of T and M, Eqn (4) is inconsistent with the results of Becker and Sallans.[12]

A further drawback of the Schreiber model, Eqn (4), is that its coefficients were derived from thin-layer drying data. There will have been gradients of both moisture and temperature within the grains in such thin layer experiments that would not be reproduced in larger bulks, because such grain would dry more slowly than in thin layers. But any consequence of this difference for quality loss cannot be determined using Schreiber's model.

In the present work, exposed layers were dried at constant air conditions and their weights and temperatures were recorded throughout. Thus, the moisture and temperature histories of the samples were known precisely. A quality loss model was devised which, by the use of diffusion equations to model heat and mass transfer during drying, accounted for the temperature and moisture distribution within the kernel.

3. Experimental details

3.1. *Apparatus*

Fig. 1 shows a schematic diagram of the dryer. Two aspects of the apparatus were essential to this work. First, the condition of the air supplied to dry the sample had to be

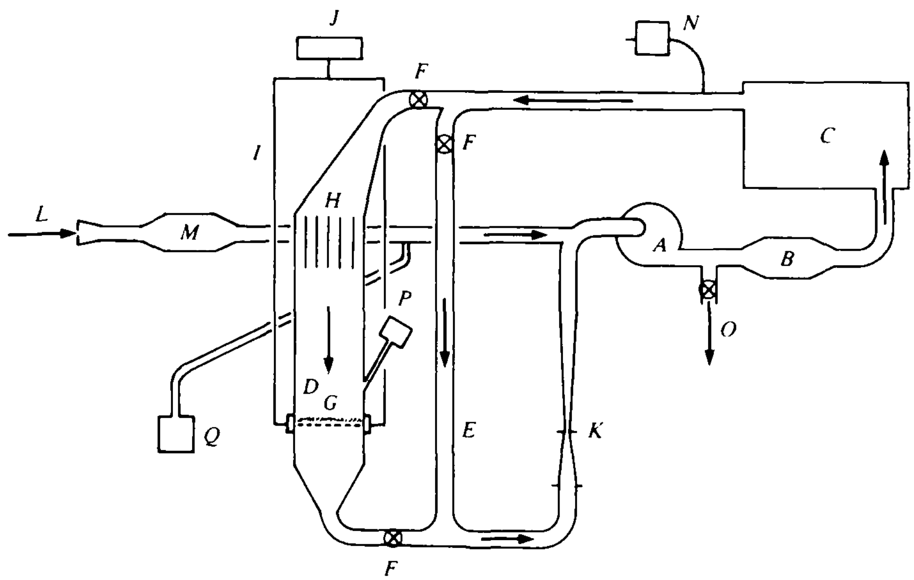

Fig. 1. Schematic drawing of the drying apparatus which had an overall height of 4·5 m. The components are approximately to scale. The direction of airflow is indicated by arrows. (A) Fan. (B) 14 kW electric heater. (C) Reservoir of 4·5 m^3 to increase air volume in the dryer. (D) Sample chamber, 0·5 m. (E) Bypass. (F) Flow control valves. (G) Grain sample. (H) Flow straightener. (I) Suspension rods. (J) Balance. (K) Venturi for air flow measurement. (L) Air inlet. (M) 9 kW electric heater. (N) Dewpoint hygrometer. (O) Air exhaust. (P) Infra-red pyrometer. (Q) Steam generator

constant and repeatable so that successive samples were subjected to drying treatments which were as identical as possible. Secondly, the drying history, i.e. moisture content and temperature of each sample, had to be measured accurately and recorded.

The apparatus used to ventilate the samples with conditioned air and to record their weight and temperature during drying is described by Bruce and Sykes[21] and Bruce.[17]

The dryer was able to dry a sample of up to 1·2 kg of wheat on a 0·2 m^2 horizontal, circular, mesh-bottomed pan exposed to a downward flow of air at a preset temperature, humidity and speed. During drying the weight of the sample was measured to within 0·05 g on an electronic balance and the surface temperature of the sample was sensed by an infrared pyrometer. To overcome the effect of airflow on the apparent sample weight, valves to divert the airflow away from the sample were actuated automatically at pre-set times thus enabling the data logger to record a "true" sample weight. A complete description of the apparatus was given by Bruce.[22] Modifications and enhancements made to the dryer since Ref. 17 was published are summarized below.

The apparatus had been improved in three major ways. First, the friction-free support system for the sample pan was improved: four air bearings, which had previously been housed within the drying chamber and thus had been subjected to the full air temperature, were relocated outside the chamber and equally spaced around the circumference, where they could more easily be inspected, adjusted and cleaned (*Fig. 2*). With the bearings operating and a constant mass on the sample pan, a series of readings was taken from the balance between each of which the airflow was directed onto and then away from the sample chamber. In this realistic situation the readings had a standard deviation of 0·06 g. The mean of ten determinations of an accurate 200 g mass, calculated

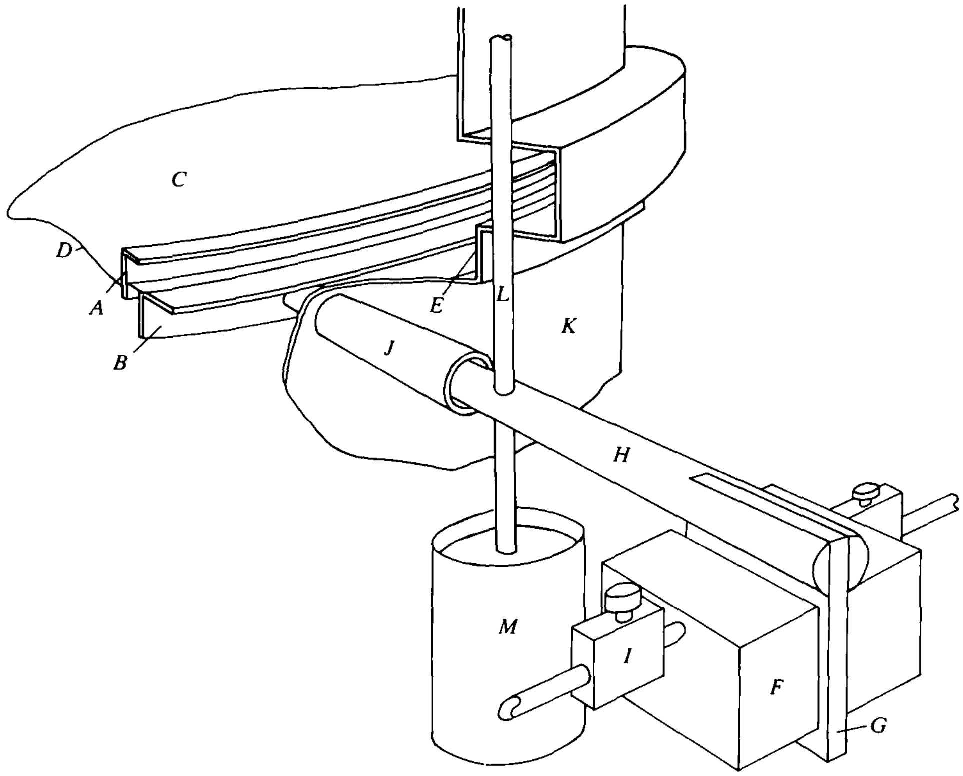

Fig. 2. Perspective view in partial section of one of the four air bearings which give friction-free support to the sample. (A) Sample pan, 0·5 m diameter. (B) Pan support ring. (C) Sample. (D) Mesh. (E) Clearance, 2 mm. (F) One of two blocks forming the bearing. (G) Fin. (H) Rod attached to ring B. (I) One of two needle valves, through which compressed air is supplied to blocks F. (J) Tube. (K) Dryer wall. (L) Support rod from balance with a piston at its lower end. (M) Oil-filled pot enclosing piston

as the difference between a reading with the mass on the sample pan and a reading with it removed, was 200·01 g with a standard deviation of $9{\cdot}8 \times 10^{-5}$ g.

Second, a boiler was installed to generate steam for humidification of the drying air and, to measure the air dewpoint for control and recording, a dewpoint sensor was installed and supplied with air drawn from the dryer upstream of the sample chamber. The air passed through a counterflow, water jacket heat exchanger consisting of two concentric copper tubes before it reached the sensor. By controlling the temperature of water circulating in the exchanger jacket the air could be kept above its dewpoint to ensure no condensation before the humidity was measured. Alternatively, if the dryer was being operated at an elevated temperature the air could be cooled to $<$100°C to prevent damage to the sensor.

Third, a computer program was written to advise the user on what settings, predetermined by experiment, to use for heater power, steam rate, air inlet rate and the parameters of the four PID (proportional integral differential) controllers. This allowed the dryer to be started up more quickly or changed from one air condition to another. Starting values of the controller parameters were calculated using the Zeigler-Nichols method[23] and improved by experiment.

3.2. *Air and grain conditions used*

Experiments were carried out in two successive years. The first pilot study used winter wheat, variety Avalon, which is a class I breadmaking variety in the UK classification,[24] and the second more extensive study used spring wheat, variety Broom, a class II breadmaking wheat. In the first case the wheat, which was harvested at a moisture content (m.c.) of approximately 0·165 dry basis (d.b.), was divided into three lots and rewetted by the addition of distilled water to give three levels of moisture. This rewetting was followed by continuous mixing for 24 h and storage at 10°C until, 12 h before the start of the test, the sample to be used was brought into the laboratory.

In the second study, the wheat was harvested on three separate occasions while naturally moist and was not artificially wetted or dried. In both cases three initial moistures were used, approximately 0·22, 0·25 and 0·28 d.b. Tables 1 and 2 show, for each of the two varieties, Avalon and Broom, respectively and for each run, the drying air temperature, the initial and final wheat moisture content, and the drying time.

3.3. *Method*

The following procedure was devised to give samples with progressively increasing amounts of damage. At each drying air condition, one sample was dried until its weight loss indicated a m.c. of 0·16 d.b. From its drying curve, times were read off for seven (for Avalon) or five (for Broom) intermediate m.c.'s at equal intervals between the initial m.c. and 0·16 d.b. Samples were then dried for these times to give, for Avalon, a total of eight drying treatments, one control rewetted but not dried and one control not rewetted, and for Broom, six drying treatments, plus one control undried sample. "Undried" indicates no drying with heated air, but these samples were reduced to storage m.c. with cool air.

To produce sufficient flour to bake a 400 g test loaf and to provide samples for m.c. and germination tests, around 1 kg of wheat was required. Because the sample pan of 0·2 m^2 could hold only 600 g in a single layer, each run with Avalon was replicated and the samples were combined. However, later tests showed that up to 1200 g in a double layer of kernels could be dried without affecting the drying rate, so for Broom each run was done only once.

The procedure for insertion and removal of samples was straightforward and has been described previously.[17] At the end of each run a 30 g sample for m.c. determination by oven drying[25] was taken, and the rest of the grains were cooled rapidly with air at around 20°C to minimize further heat damage. When cool they were transferred to an ambient air dryer and left to reach a m.c. of 0.15–0.16 d.b. and subsequently stored in sealed containers at 10°C until despatched for baking tests.

During drying, sample mass and surface temperature were recorded at 5 s intervals until 300 s into the run, and at 30 s intervals thereafter. Most of the weights were recorded during drying so the weight logged represented the sample weight plus an additional force caused by the pressure difference required to drive the flow of drying air through the sample. "True" weights were also recorded, after the drying air had been diverted for 5 s, at intervals increasing from 30 to 300 s, so that the effect of air pressure could later be eliminated from the weight data. In subsequent analysis it was shown that the "air off" weights alone gave estimates of model parameters as accurate as were achieved using all weights.

Dried samples were sub-sampled and tested for viability,[26] and then milled and baked into test loaves by the long fermentation process.[2] This method was preferred to the Chorleywood MDD (Mechanical Dough Development) process[2] by which the major proportion of UK bread is made because MDD is known to be more tolerant of thermally

Table 1
Results for wheat of variety Avalon

Run No.	Mean air dry bulb temperature, °C	Mean air dewpoint temperature, °C	Mean initial m.c., dec. d.b.	Mean final m.c., dec. d.b.	Drying time, s	Final viability, %	Loaf volume, cm^3	Loaf relative volume Eqn (5)
Note: Air dewpoint temperature = ambient (not controlled). Hyphen indicates not applicable or not tested.								
Controls*								
C1	—	—	0·166	—	0	99	1275	—
C2	—	—	0·164	—	0	99	1175	—
C3	—	—	0·215	—	0	99	1245	—
C4	—	—	0·249	—	0	99	1240	—
C5	—	—	0·278	—	0	100	1245	—
* C1, C2 not rewetted, C3, C4, C5 rewetted from 0·165 d.b.								
					Mean of rewetted controls 1245			
25				0·210	70	99	—	—
26				0·202	120	99	—	—
27				0·198	190	98	—	—
28	69·9	12·5	0·221	0·190	265	99	—	—
29				0·185	350	99	—	—
30				0·178	465	99	—	—
31				0·174	585	—	—	—
32				0·166	750	98	—	—
33				0·240	95	99	—	—
34				0·226	180	99	—	—
35				0·215	260	—	—	—
36				0·206	365	99	—	—
37	69·9	15·3	0·255	0·195	510	—	—	—
38				0·186	680	99	—	—
39				0·176	880	—	—	—
40				0·167	1120	99	—	—
41				0·260	105	—	—	—
42				0·246	190	99	—	—
43				0·232	305	—	—	—
44				0·217	450	99	—	—
45	69·8	16·5	0·280	0·206	625	—	—	—
46				0·189	850	96	—	—
47				0·174	1200	—	—	—
48				0·163	1410	99	—	—
49				0·208	55	98	—	—
50				0·197	95	97	—	—
51				0·194	140	93	—	—
52	80·1	14·1	0·216	0·188	195	86	1185	0·952
53				0·180	270	59	1175	0·944
54				0·173	350	53	1175	0·944
55				0·169	435	21	1095	0·880
56				0·160	540	40	1145	0·920
57				0·235	65	98	—	—
58				0·223	120	85	1215	0·976
59				0·211	180	63	1175	0·944
60	80·1	13·4	0·249	0·199	260	27	1095	0·880
61				0·192	355	20	1095	0·880
62				0·182	475	9	1055	0·847
63				0·172	620	2	1015	0·815
64				0·159	795	4	975	0·783

Table 1
(Continued)

Run No.	Mean air dry bulb temperature, °C	Mean air dewpoint temperature, °C	Mean initial m.c., dec. d.b.	Mean final m.c., dec. d.b.	Drying time, s	Final viability, %	Loaf volume, cm^3	Loaf relative volume Eqn (5)
65				0·250	85	89	1235	0·992
66				0·246	150	57	1215	0·976
67				0·229	230	8	1065	0·855
68	80·2	14·4	0·282	0·216	330	3	995	0·799
69				0·198	455	1	915	0·735
70				0·184	610	1	855	0·687
71				0·175	790	1	840	0·675
72				0·161	1005	0	845	0·679

Table 2
Results for wheat of variety Broom

Run No.	Mean air dry bulb temperature, °C	Initial m.c., dec. d.b.	Final m.c., dec. d.b.	Drying time, s	Final viability, %	Loaf volume, cm^3	Loaf relative volume, Eqn (5)
NOTE: Air dewpoint temperature 13·0°C during all runs							
Controls							
C18/1	—	0·220	—	0	96	1205	1·0
C18/2	—	0·220	—	0	96	1285	
C20/1	—	0·250	—	0	96	1235	1·0
C20/2	—	0·250	—	0	93	1245	
C22/1	—	0·282	—	0	92	1240	1·0
C22/2	—	0·282	—	0	91	1260	
					Control mean	1245	
73			0·118	4200	96	1235	0·992
74	64·5	0·220	0·102	7200	94	1235	0·992
75			0·088	14400	97	1215	0·976
76			0·142	2400	94	1245	1·004
77	64·5	0·251	0·117	4800	93	1285	1·037
78			0·106	7200	94	1235	0·996
79			0·151	2400	89	1330	1·068
80	64·5	0·285	0·107	7200	89	1300	1·009
81			0·165	720	96	1245	1·000
82			0·142	1500	96	1235	0·992
83	70·0	0·220	0·124	3300	93	1285	1·032
84			0·100	6000	93	1245	1·000
85			0·085	12000	95	1235	0·992
86			0·191	540	91	1260	1·016
87	70·0	0·252	0·164	1140	94	1245	1·004
88			0·134	2400	87	1310	1·052
89			0·104	6000	83	1240	1·000
90			0·244	300	89	1270	0·987
91			0·208	540	90	1270	0·987
92	70·0	0·284	0·176	1140	81	1240	0·965
93			0·141	2400	72	1260	0·979
94			0·105	3600	60	1240	0·965

Table 2

(Continued)

Run No.	Mean air dry bulb temperature, °C	Initial m.c., dec. d.b.	Final m.c., dec. d.b.	Drying time, s	Final viability, %	Loaf volume, cm^3	Loaf relative volume, Eqn (5)
95	75·0	0·221	0·180	300	92	1235	0·992
96			0·161	660	89	1240	0·996
97			0·140	1260	86	1200	0·964
98			0·119	2400	84	1220	0·980
99			0·107	3600	80	1210	0·972
100	74·8	0·251	0·198	330	79	1210	0·976
101			0·177	660	64	1180	0·951
102			0·150	1260	72	1170	0·943
103			0·126	2400	53	1180	0·951
104	74·5	0·283	0·252	150	91	1260	0·979
105			0·221	330	53	1250	0·972
106			0·192	660	59	1140	0·890
107			0·160	1260	29	1145	0·894
108			0·129	2400	26	1125	0·879
109	80·2	0·220	0·203	90	97	1225	0·984
110			0·190	180	81	1200	0·964
111			0·178	300	58	1170	0·940
112			0·160	540	33	1155	0·928
113			0·138	1080	45	1095	0·879
114	80·1	0·252	0·232	90	95	1235	0·996
115			0·212	180	49	1210	0·976
116			0·196	300	21	1125	0·907
117			0·177	540	7	—	—
118			0·150	1080	2	—	—
119	80·1	0·284	0·262	90	86	1310	1·017
120			0·236	180	28	1185	0·924
121			0·218	300	3	—	—
122			0·193	540	0	—	—
123			0·158	1080	0	—	—
124	85·1	0·221	0·202	90	86	1260	1·012
125			0·185	180	26	1155	0·928
126			0·174	300	4	—	—
127			0·160	480	0	—	—
128			0·137	720	0	—	—
129	85·2	0·252	0·227	90	72	1230	0·992
130			0·208	180	6	—	—
131			0·191	300	1	—	—
132			0·175	480	0	—	—
133			0·159	720	0	—	—
134	85·2	0·284	0·265	60	81	1290	1·002
135			0·248	120	17	—	—
136			0·219	480	0	—	—
137			0·191	960	0	—	—

damaged wheat (Hook, S. C. W. personal communication). The test loaf method had a standard error of volume determination (by immersion in rapeseed) of 13 cm^3 (approximately 1% of the volume of a good quality test loaf) for samples from the same dough mix, and 19 cm^3 for replicate mixes. A dough mass of 454 g was used for each loaf.

4. Results of experiments

Tables 1 and 2 show air conditions, initial and final moisture content, drying time, the viability of the dried samples, the volumes of test loaves baked from the samples and the volume ratio, V_r. For the pilot study using Avalon, it was possible to have only a limited number of samples milled and baked into test loaves. Samples to be tested for baking quality were selected on the basis that high viability was an indication of undamaged baking quality, and so only the controls and most of the samples dried with 80°C air were tested. In the main study with Broom all samples except those showing less than 20% viability were tested for baking quality. The baking volume of the controls of both varieties was not as high as would be expected from first class wheat samples, which would give volumes of around 1500 cm^3 for 454 g of dough. Nevertheless the volumes showed the expected pattern of deterioration. The viability of the highest moisture Broom sample was poorer than expected for a freshly harvested sample. The viability values were closely correlated with baking volume, as demonstrated by a simple regression model which was fitted to data between 20 and 100% viability, (*Fig. 3.*). Though the regression model is not ideal, because its use implied that all the error is in the values of V_r and not in G, it does show that V_r and G are closely related, and that the loss of viability is more rapid than the loss of loaf volume.

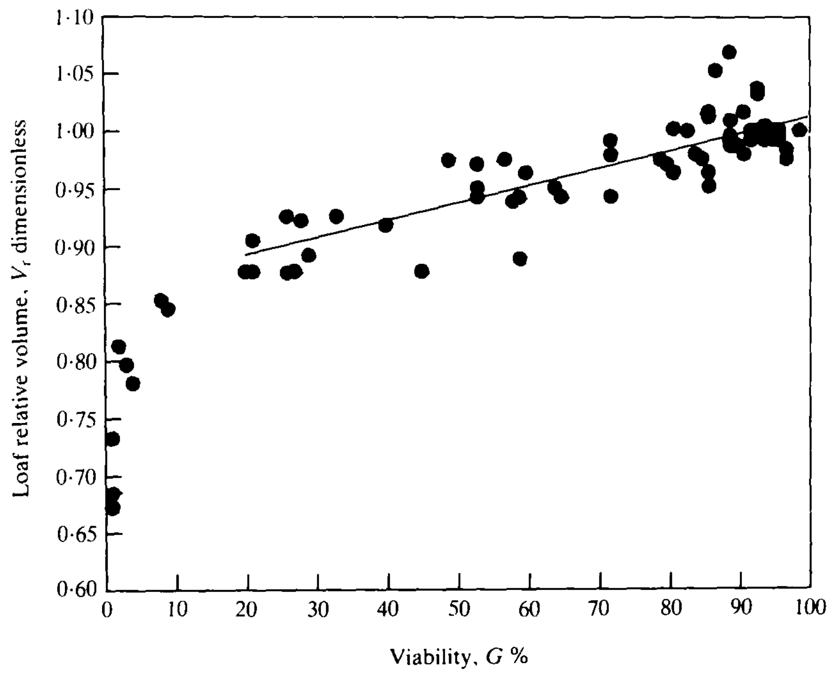

Fig. 3. Loaf relative volume, V_r, versus viability, G, for all runs of the present work for which V_r was determined. The linear regression was only applied to samples with viability ≥20%. The regression line given by $V_r = 1470G + 0{\cdot}863$ accounts for 73% of the variance in V_r

At each combination of initial m.c. and air temperature, the samples were subjected to similar drying treatments, and so to simplify analysis, initial portions of the moisture and temperature record for the sample with the longest drying time were used to represent the drying conditions for shorter runs.

Comparing the drying rate with 80°C air of samples with three initial moisture levels from both Broom and Avalon data sets showed that the two samples dried at similar rates (*Fig. 4*). This was not necessarily expected because kernels in the two samples were of dissimilar size, and the smaller kernels, Broom, would be expected to dry more rapidly because of its greater specific surface area and shorter path for moisture to reach the kernel surface. However, the artificial rewetting of the Avalon sample could have resulted in faster drying than for Broom. Samples of wheat artificially rewetted with liquid water were found by Wassermann *et al.*[18] to dry significantly quicker than naturally moist samples or those remoistened by absorption of vapour. *Fig. 4* also includes data points from the work of Wassermann *et al.*[18] and shows that the drying of their wheat was initially much slower for the same drying air temperature and similar initial moisture contents. It is likely that the 5 kg sample used by Wassermann formed a layer sufficiently thick that some of the grains were exposed not to the inlet drying air but to cooler and more humid air. Compared to the behaviour of a thin layer, this would have reduced the overall drying rate of the sample and reduced the rate of temperature rise. *Fig. 5* shows evidence to support this conclusion. The measured sample temperatures for Avalon, at three initial moisture contents, exposed to 80°C air are compared with wheat temperature data from Wasserman *et al.*[18] For the same air temperature the grain temperatures are

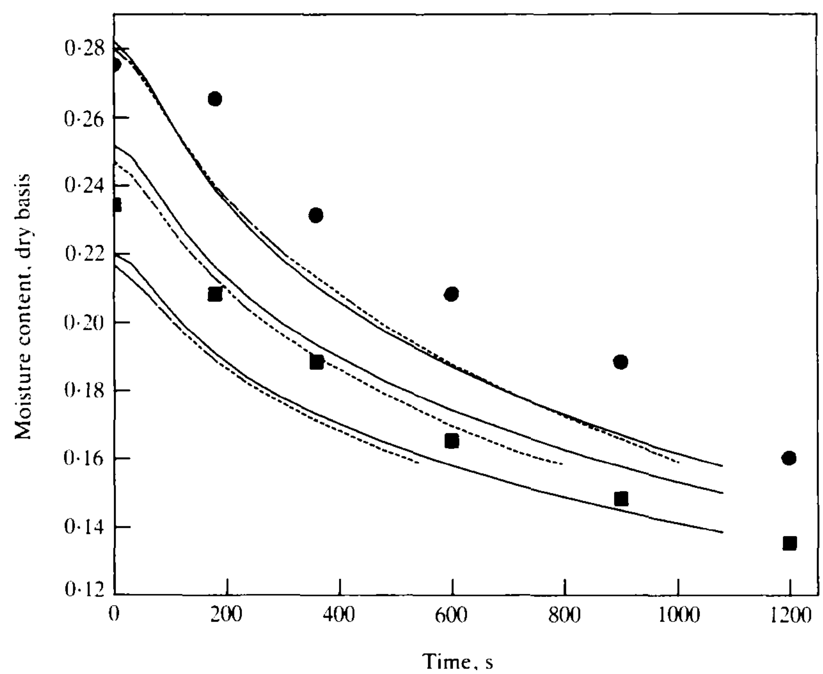

Fig. 4. Moisture content versus time for wheat of variety Avalon, (- - - - -), runs 72 (top), 64 (middle) and 56 (bottom) and variety Broom, (——) runs 123 (top), 118 (middle) and 113 (bottom) from the present work. Drying air temperature was ≈80°C, (for other details see Tables 1 and 2). Points are data from Wassermann et al[18] *drying Jubilar wheat of initial m.c. 0·276 d.b. (●) and 0·235 d.b. (■) with air at 80°C*

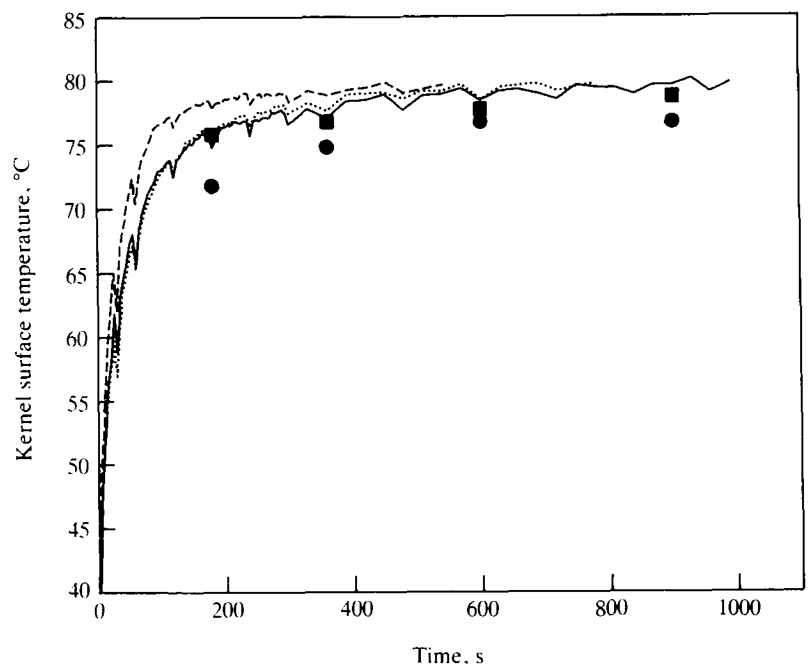

Fig. 5. Grain surface temperature versus time for wheat of variety Avalon, runs 56, (----), 64 (......) and 72 (——) Points are data from Wassermann et al[18] *drying Jubilar wheat with air at 80°C. Initial m.c.: ● 0·276, ■ 0·234*

higher in the thin layers of the present work. The consequences of these differences in grain moisture and temperature for the analysis of the effect on baking quality are discussed in Section 5.

To make the data independent of loaf mass, Schreiber *et al.*[20] converted the data of Wassermann *et al.*[18] to specific volume, defined as volume per unit mass. An alternative means of normalizing the loaf volumes would be to divide each volume or specific volume by that of the control to give relative volume or relative specific volume respectively. The mass of each test loaf of the present work was therefore determined. Because the loaves had been frozen in paper sacks for storage, moisture loss had occurred, and the masses of the loaves were not consistent. Therefore, the conversion to specific volume was not used. However, because in this work the mass of dough for each loaf including the controls was identical, 454 g in each test, the relative volume and relative specific volumes would only have differed from each other because of any differences, likely to be small, in loaf masses after baking. Therefore relative volume as used in this work and relative specific volume as used by Schreiber *et al*[20] should be comparable.

Figs 6 and *7* present experimental data of loaf relative volume versus drying time for the combined Avalon and Broom series at initial moistures of approximately 0·28, and 0·25 d.b. respectively. No significant reduction in loaf relative volume was observed with 65°C drying air temperature until 4 h, but progressive damage with time was evident at air temperatures of 75°C and above for initial moisture contents of (and below, not shown in figures) 0·25, and at 70°C and above for the wheat of 0·28 initial moisture. At a given drying air temperature damage occurred more rapidly in higher m.c. samples.

For comparison, *Fig. 8* shows the relative specific volume data of Wassermann *et al.*[18]

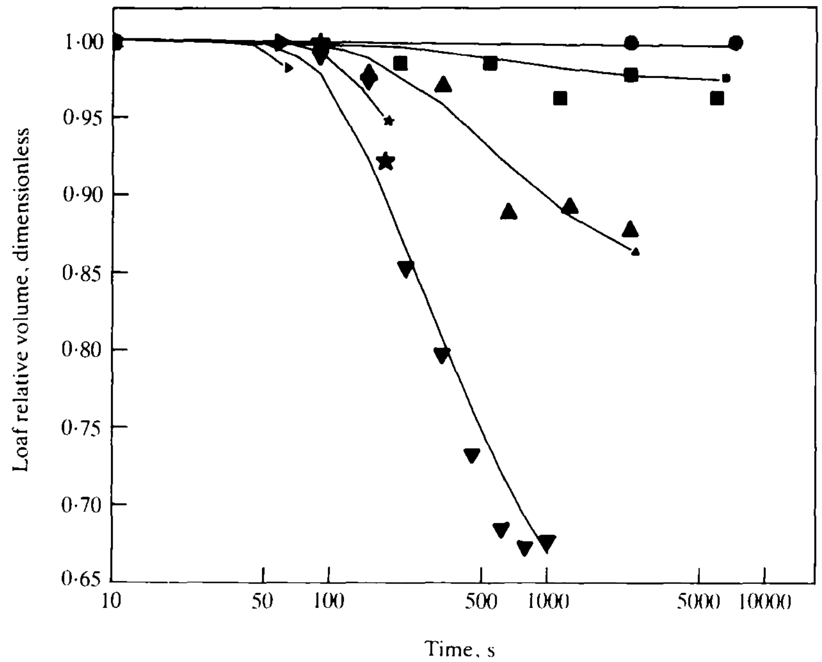

Fig. 6. Experimental observations (symbols) and predictions (lines) of loaf relative volume for loaves baked from wheat samples dried in thin layers for various times. The predictions were made using Eqn (10). Wheat initial m.c. ≈0·28 d.b. All samples were of variety Broom except where indicated. Smaller symbols identify lines. ● 65°C, ■ 70°C, ▲ 75°C, ▼ 80°C Avalon variety, ★ 80°C, ▶ 85°C

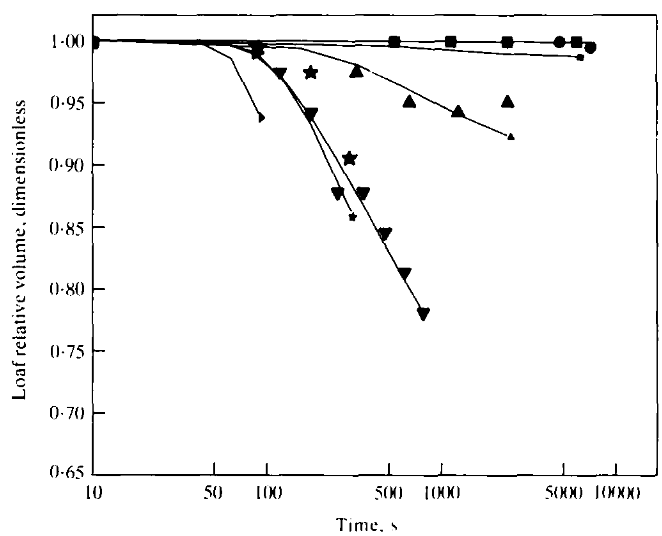

Fig. 7. Experimental observations (symbols) and predictions (lines) of loaf relative volume for loaves baked from wheat samples dried in thin layers for various times. The predictions were made using Eqn (10). Wheat initial m.c. ≈0·25 d.b. All samples were of variety Broom except where indicated. Smaller symbols identify lines. ● 65°C, ■ 70°C, ▲ 75°C, ▼ 80°C Avalon variety, ★ 80°C, ▶ 85°C

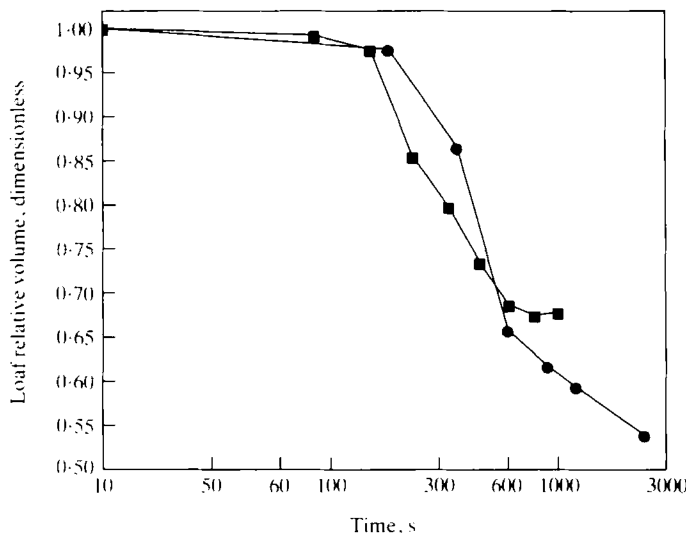

Fig. 8. Comparison of experimental observations of loaf relative volume for loaves baked from wheat samples dried for various times. Key; ■, *Data of the present work (runs 65–72);* ●, *Data of Wassermann* et al[18]. *Drying air temperature ≈80°C. Initial m.c. ≈0·28 d.b.*

plotted together with loaf relative volumes from the present work. Drying air temperature was 80°C in both cases, and the initial grain moisture contents differed by only 0·008 m.c. dry basis. Though the variety of wheat (Jubilar) used by Wassermann and baking method differed, the overall pattern was very similar and the curves exhibited similar variability.

Fig. 9 shows the effect of increasing duration of drying on five cut loaves baked from wheat dried at 80°C (runs C5, 65, 67, 69 and 71 in Table 1) showing, in addition to the reduction in volume, lightening of the crust colour and coarsening of the crust. Crumb structure also deteriorated though this is not evident in *Fig. 9.*

5. Analysis

Two stages of analysis were required. First, a model was needed to describe the heating and drying behaviour of the grains. This was used to predict moistures and temperatures

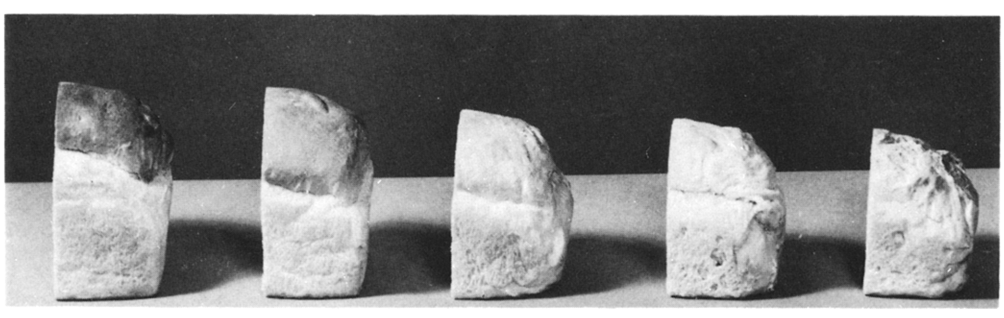

Fig. 9. Effect of increasing the duration of thin layer drying of wheat with air at 80°C on the size, crust, texture and colour of loaves baked from the wheat. From left to right, run nos. C5, 65, 67, 69 and 71

of grain kernels for use in quality loss calculations. Secondly, a model was needed to describe quality deterioration as a function of grain moisture and temperature. These two stages are described separately.

5.1. *Model of physical behaviour of grains during drying*

Drying and heating behaviour of single grain kernels (or thin layers of kernels) can be described very closely by models of the diffusion of moisture and the conduction of heat within the kernel. Besides enabling the physical data to be closely represented this approach also enables the contributions to loss of loaf relative volume from various regions within the kernel to be taken into account. The model employed here was described by Bruce[17] who used it to model barley drying. The model, which had three semi-empirical coefficients, was based on a ten-shell representation of a spherical particle with evaporation from the surface and finite difference calculation of moisture transport by diffusion within the sphere. The diffusion coefficient was dependent on moisture concentration. To model heat transfer the model of Sokhansanj and Bruce[16] was used. This model included air-to-surface heat transfer, cooling caused by evaporation of moisture at the surface, and conduction of heat within the particle, again represented as a ten-shell sphere.

The ten-shell sphere drying model was fitted to the moisture loss data of each drying run by determining the optimum values, in the least squares sense, of the three coefficients. The model fitted each set of measured moisture loss data closely, accounting for a mean over the runs of 94·6% of the variance of the data. The heating model, not fitted to the data in any way, accurately predicted the temperatures of the grain surface (*Fig. 10*).

The moisture and temperature of each shell of the ten-shell model and for the kernel as

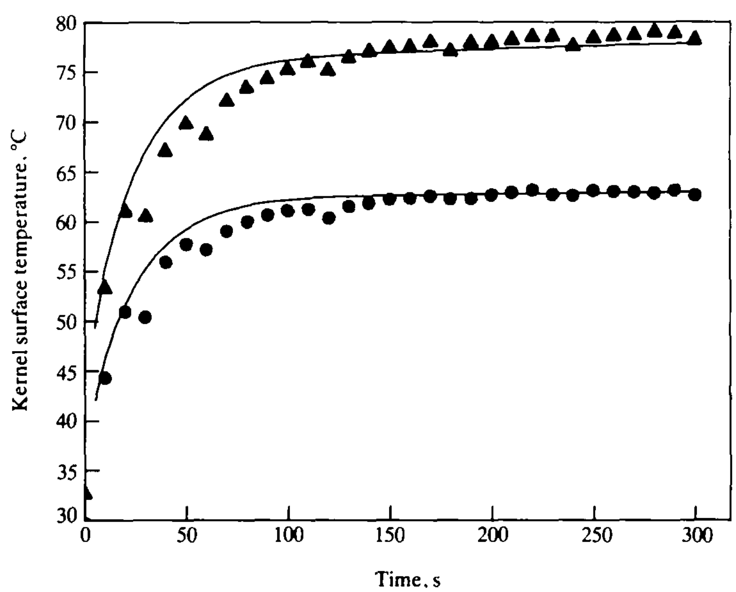

Fig. 10. Grain surface temperature versus time. Lines-predicted by the model of Sokhansanj and Bruce[16] in conjunction with the mass transfer model of Bruce.[17] Symbols-measured in the present work. The two runs shown are 118 (▲) and 78 (●)

a whole was calculated using the model for each 5s step throughout each drying run for use in calculations of deterioration.

5.2. *Model of deterioration of loaf relative volume*

It was necessary to transform each observation of loaf volume, V, into a relative volume defined as

$$V_r = \frac{V}{V_c} \tag{5}$$

so that the data from several samples and from two years' experiments could be combined. An alternative expression, Eqn (6), was used to take into account the residual loaf volume,

$$V_n = \frac{V - V_u}{V_c - V_u} \tag{6}$$

This results in a normalized loaf volume which equals unity at $V = V_c$ and reduces to 0 at $V = V_u$ and is therefore preferable to a parameter such as V_r which has a non-zero asymptote, the value of which is dependent on the value V_c. However, it was found that the use of V_n resulted in a much poorer fit of the quality loss models to the observed data, and poor comparability between the data of Wassermann *et al.*[18] and those of the present work. A possible explanation of why Eqn (1) is more successful at describing the data than Eqn (6) is given in Appendix 1.

Consider the deterioration of loaf relative volume as a function of the temperature and moisture during drying of the wheat kernels from which the loaf was made. Two models of loaf volume loss were used to determine which best described the observations; (1) a zero-order model, Eqn (4), in which the rate of loss of relative volume is *constant* at given kernel moisture and temperature, but increases exponentially with both these variables and (2) a first-order model, Eqn (1) in which the rate of loss of relative volume is *logarithmic* at given kernel conditions.

The Arrhenius relationship, Eqn (2), was used to describe k of Eqn (1) and k_0, the value of k at absolute zero, was represented by a linear function of moisture content, Eqn (7) as suggested by Nellist.[13]

$$k_0 = c + eM \tag{7}$$

Hence, in this second model the rate of volume loss increases non-linearly with temperature but linearly with moisture.

5.3. *Method of use of the models*

The first approach was to use only the kernel mean temperatures and moistures. These were calculated by Simpson's rule from the shell temperatures and moistures, predicted by the model described in Section 5.1. For each 5 s time increment throughout a particular run, the calculated values of moisture and temperature for the kernel as a whole were used to calculate the incremental loss of V_r which was then deducted from the current value of V_r. Thus at each time when an observation of V_r was available an error between calculated and observed V_r was obtained. This process was continued throughout the run, and then repeated for all 112 runs. An overall sum of squares of errors was then minimized using a function minimization routine[27] to refine the initial estimate of coefficients of deterioration model.

The above process was carried out for both deterioration models, namely Model 1 comprising Eqns (1), (2) and (7) and Model 2 comprising Eqn (4). The models, with their best fit coefficients, were

$$-\frac{dV_r}{dt} = \exp(-44{\cdot}1 + 0{\cdot}364T + 37{\cdot}4M) \tag{8}$$

for which the residual sum of squares for all 112 runs was $3{\cdot}86 \times 10^{-2}$ and, combining Eqns (1), (2) and (7),

$$-\frac{dV_r}{dt} = V_r \exp[115 + 38{\cdot}1M - 381000/(R\theta)] \tag{9}$$

for which the residual sum of squares was $4{\cdot}03 \times 10^{-2}$.

A second approach was then taken. The procedure followed was exactly as described above for the whole grain, except that the deterioration was calculated independently for each shell, using the moistures and temperatures calculated by the ten-shell diffusion model. At each time where an observation of V_r had been made, the mean V_r for the whole sphere was calculated using Simpson's rule. The contribution to the loaf relative volume of each shell, V_{rs}, was weighted by the relative mass of that shell. Calculated and observed values of V_r were then used to form a sum of squares.

A problem arose with the calculation of deterioration near the centre of the sphere where the temperature approached that of the drying air before the moisture had fallen significantly. Under these conditions, which would occur in practice, for example, at the inlet face of a simple cross-flow dryer, a high rate of deterioration was predicted by both models of quality loss. With Model 2, Eqn (4), the predicted quality in the central shells became negative and so this quality loss model was not usable within the ten-shell calculations. Model 1, consisting of Eqns (1), (2) and (7), gave satisfactory results because it predicts logarithmic not linear deterioration.

The result of minimizing the sum of squares of errors between predicted and measured loaf relative volume can be expressed, by combining Eqns (1), (2) and (7), as

$$-\frac{dV_{rs}}{dt} = V_{rf} \exp[130 + 41{\cdot}4M_s - 427000/(R\theta_s)] \tag{10}$$

The residual sum of squares for all 112 runs was $2{\cdot}46 \times 10^{-2}$.

Either Eqn (8) or (9) would be adequate to describe the observed loss of baking quality, although if the damage to quality was small, Eqn (8) was slightly better at describing the data. However, Eqn (9) is preferable overall because it has a more realistic asymptote. Eqn (10), applied to each of the ten individual shells of the kernel model, represents the observed data more closely than Eqns (8) or (9) and is more likely to give accurate predictions of loaf volume loss where the moisture and temperature distribution in the grain does not follow that of an exposed layer, e.g. in mixed-flow dryers in which rewetting by condensation or by adsorption may occur, or in concurrent-flow dryers in which periods of intense drying alternate with resting periods.[9]

Figs 6 and *7* show the good agreement between measured values of loaf relative volume and predictions made by applying Eqn (10) to the shells.

5.4. *Verification*

To test Eqn (10) on independent data, values of grain moisture and temperature from Wassermann *et al.*[18] were used. For each of four runs, spanning two initial moisture contents and four drying air temperatures, the diffusion model of Bruce[17] was fitted to

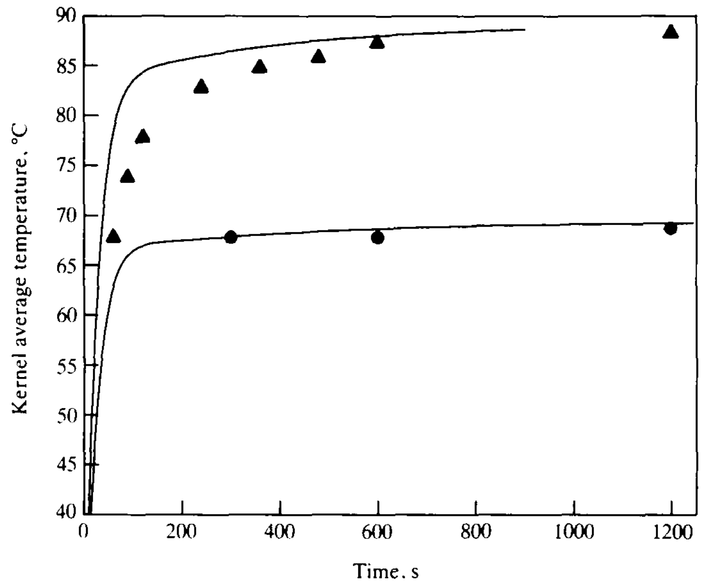

Fig. 11. Grain mean kernel temperature versus time. Symbols – data of Wassermann et al.[18] *Lines – predictions for Wassermann's runs by the model of Sokhansanj and Bruce*[16] *in conjunction with the mass transfer model of Bruce.*[17] *Predictions are satisfactory for 70°C drying air temperature (●) but temperature rise was slower than predicted at 90°C (▲)*

Wassermann's data of moisture versus time. Mean grain temperatures predicted by the heating model of Sokhansanj and Bruce[16] were found to be close to Wassermann's values for 70 and 80°C treatments, but at 90 and 100°C, the predicted temperatures were high (*Fig. 11*). This had a significant effect on the prediction of Wassermann's loaf volumes (see below). Eqn (10), together with the calculated shell moistures and temperatures, was used to predict the values of V_{rs} for each shell throughout Wassermann's four runs. As before at each observation time and at additional times for plotting purposes the mean V_r for the whole grain kernel was computed by Simpson's rule. Wassermann's loaf volume data, published in units of cm^3/g, was converted to relative volume by dividing by his control volume, also in cm^3/g.

Results of this exercise are shown in *Fig. 12.* Virtually no damage is predicted drying with air at 70°C while a small amount was observed. At 80°C the observed damage is well predicted, particularly after 500 s of drying. At times shorter than this and at air temperatures of 90 and 100°C, predicted damage is more severe than Wassermann observed. Considering the differences in baking method, wheat variety and experimental apparatus, the predictions at 70 and 80°C are reasonably good. Part of the explanation for differences at higher temperatures may be that, as noted earlier and shown in *Fig. 11,* the heating rate of the grain in Wassermann's work was slower than in this work. This means that a given exposure time would have been less damaging to Wassermann's samples than to those reported here. During the first 500 s of the 90°C treatment in *Fig. 11,* for example, the mean difference between measured and predicted grain temperature was 5·0°C, i.e. air temperature was effectively 85 rather than 90°C. In *Fig. 12* the observed points for the 90°C treatment lie between the 80 and 90°C predicted lines, suggesting that the agreement would have been improved had the intra-kernel temperatures of Wassermann's grain been better modelled.

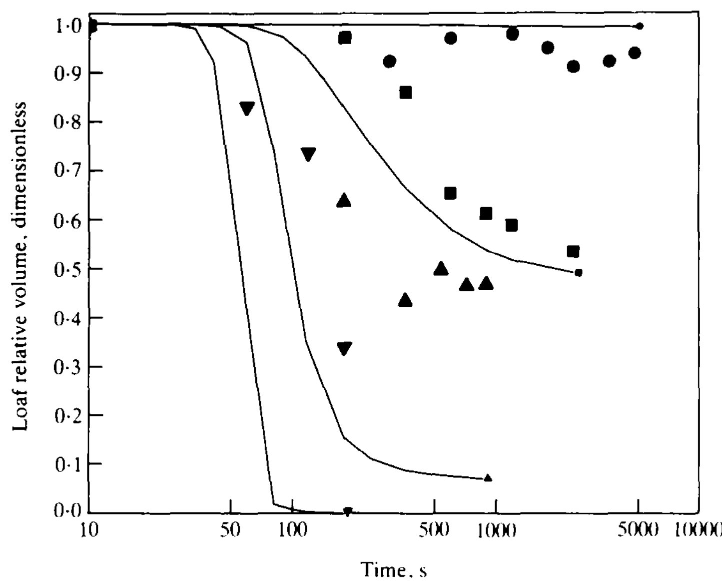

Fig. 12. Loaf relative volume versus time. Symbols show data of Wassermann et al[18] *for drying with air temperature of 70 (●), 80 (■), 90 (▲) and 100°C (▼). Initial moisture was 0·234 for 70°C, and 0·276 for other runs. Small symbols identify the corresponding predicted lines*

However, it may be that the intra-kernel temperatures were well predicted and that the reason for the discrepancy shown in *Fig. 12* lay elsewhere. In that case, the predictions of the model are seen to be somewhat too severe. This may not be a serious drawback because it would result in a margin of safety when using the model for design purposes.

The grain temperature range for which Eqns (8) to (10) were derived, and are therefore directly applicable, was from 65°C, at which thermal damage was observed to begin, to 85°C. However, in some types of dryer, e.g. mixed-flow and concurrent-flow, the grain temperature is known[9] not to approach closely to the inlet air temperature so Eqns (8) to (10) could be used for calculating damage to baking quality at inlet air temperatures considerably higher than 85°C. Eqns (8) to (10) are applicable over a moisture range of 0·10 to 0·28 d.b.

Further work is needed to confirm that the predictions of baking quality loss are valid for other varieties of wheat, and for the conditions inside a deep, perhaps moving, bed of grain where the temperature and moisture histories are complex.

Because of the non-linear effect of temperature on the rate of damage, as shown in this work, the application of the model to drying in a full-scale dryer will need to take account of variations in drying air temperature (variations in time about a mean value, and in distance over the face of the hot air plenum).

Conclusions

1. Two varieties of wheat dried in exposed layers with air temperatures from 65 to 85°C exhibited similar drying rates. They also showed similar losses of loaf volume, relative to controls, when milled and baked into test loaves. The loss of loaf relative volume was similar to previously published data.

2. The author's existing models of heating and drying, based on diffusion in a spherical particle, were able to describe the observed drying behaviour well, and thereby to calculate the moisture and temperature of each of ten shells within the sphere throughout each run.
3. The calculated moisture and temperature histories of the kernels as a whole during each drying run were then used to compute the loss of loaf relative volume in conjunction with two models of deterioration. The models were

$$-\frac{dV_r}{dt} = \exp(-44{\cdot}1 + 0{\cdot}364T + 37{\cdot}4M) \tag{8}$$

and

$$-\frac{dV_r}{dt} = V_r \exp[115 + 38{\cdot}1M - 381000/(R\theta)] \tag{9}$$

The second model was preferred because of its asymptotic form.
4. The second form of model was also used with the computed intra-kernel moistures and temperatures for ten shells of the kernel in place of the whole kernel values. The resulting model, which fitted the data very well throughout the temperature and moisture range, was

$$-\frac{dV_{rs}}{dt} = V_{rf} \exp[130 + 41{\cdot}4M_s - 427000/(R\theta_s)] \tag{10}$$

This model was also able to predict reasonably well results at 80°C air temperature published by Wassermann *et al.*[18] At 90 and 100°C deterioration predicted by Eqn (10) was faster than recorded by Wassermann *et al.* but the discrepancy was at least partly caused by the lower grain temperatures reached in the first 500 s of drying in Wassermann's experiments.
5. Eqns (8) to (10) derived for the range 75–85°C grain temperature and 0·10–0·28 d.b. moisture content, but they may be used in simulations of drying at higher air temperatures where grain temperature may remain below that of the air.
6. If Eqn (10) is used in a calculation of permissible time-temperature exposure, Wassermann's results suggest that the prediction will have a margin of safety in grain temperature between 0 and 5°C.
7. Application of these results in commercial dryers requires verification by experiments on such dryers, and will be affected by how much the drying air temperature varies in space and time over the face of the hot air plenum.

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Appendix A

In Section 5.2 it was noted that the normalized loaf volume V_n given by Eqn (6) would have been preferable to the use of relative volume V_r defined by Eqn (5). However, the data from the two varieties of wheat in the present work and that of Wassermann *et al*[18] were found to agree very well when expressed in terms of V_r but not as V_n. This observation suggests that, as bread quality of wheat falls, the decay of V_r is initially asymptotic not to the actual minimum value of V_r but to an asymptote close to zero. The following conjecture is an attempt to explain this behaviour.

Consider the gas pressure within the gluten matrix of the dough. The dough volume will be dependent upon the pressure generated within the gas cells (see schematic drawing, *Fig. 13*). For the purposes of this analysis the dough volume is considered to be equal to the final loaf volume. In a dough of undamaged protein there will be little leakage of gas and the pressure at a typical point in the dough, initially at zero relative to atmosphere, will rise until it can support the "head" of dough above (point A). A higher pressure (point B) will be needed to stretch the elastic membranes to expand the gas cells as the loaf rises. This pressure will increase as the gas production rate, and therefore the rate of extension of the membranes, increases. Once the pressure is sufficiently high, the rate of expansion will be determined by the gas production rate, and the pressure may not rise further (point C). All the samples which have risen must be between points B and C.

If the gluten matrix is not gas tight because of heat damage to the proteins during drying of the grains, the maximum pressure will be limited by gas leakage. The more severe the damage is the lower will be the maximum sustainable pressure, and the lower will be the risen volume at a given time after initial mixing of the dough. A series of samples with progressively increasing damage to proteins, such as produced by the experiments in the present work, would therefore be expected to exhibit a spread of

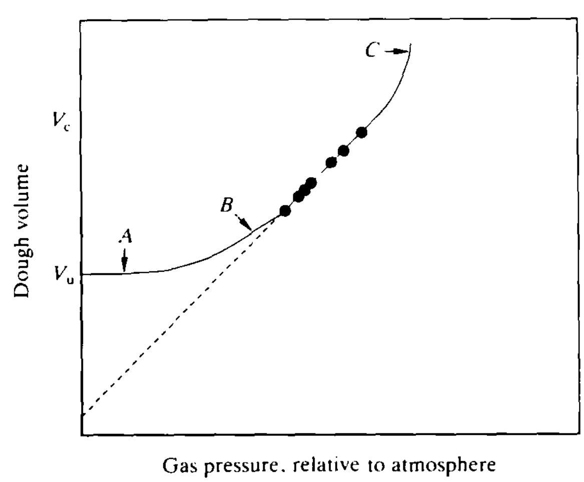

Fig. 13. Hypothetical graph of dough volume, ml, for runs C4 and 58–64 against gas pressure within the dough, for which no values were available showing how progressive damage could result in an apparently near-zero asymptote for dough volume. A, B, and C are described in Appendix A

position on the curve of schematic *Fig. 13* at the time of baking. No values were available for gas pressure but the loaf volumes for runs C4 and 59–64 were used to help draw the schematic. Extrapolation from the loaf volume values back to the extreme damage case of zero sustainable pressure could give a loaf volume approaching a value in the region of zero.

To model the dough behaviour, data would be needed on the gas production rate, rates of leakage of gas from heat-damaged gluten membranes, and viscosity and elasticity of the dough. It would then be possible to predict the pressures inside the gas cells at points between the top and bottom of the dough, and thereby to predict the volume of the dough during rising.