and insoluble-bound phenolic acids. 1. Extraction and purification procedure. J. Agric. Food Chem. 30:330.

MARTENS, M., COTTENIE-RUYSSCH, M., HANSELAER, R., De COOMAN, L., CASTELLE, K., and VAN SUMERE, C. 1988a. *N*-Feruloylglycine amido-hydrolase from barley seeds and isolated barley embryos. Phytochemistry 27:2457.

MARTENS, M., COTTENIE-RUYSSCH, M., HANSELAER, R., De COOMAN, L., CASTELLE, K., and VAN SUMERE, C. 1988b. Characteristics and specificity of purified *N*-feruloylglycine amidohydrolase from isolated barley embryos. Phytochemistry 27:2465.

McGINNIS, G. D. 1982. Preparation of aldonitrile acetates using *N*-methylimidazole as a catalyst and solvent. Carbohydr. Res. 108:284.

MEUSER, F., and SUCKOW, P. 1986. Non-starch polysaccharides. Page 42 in: Chemistry and Physics of Baking. J. M. V. Blanshard, P. J. Frazier, and T. Galliard, eds. The Royal Society of Chemistry: London.

MUELLER-HARVEY, I., HARTLEY, R. D., HARRIS, P. J., and CURZON, E. H. 1986. Linkage of *p*-coumaroyl and feruloyl groups to cell-wall polysaccharides of barley straw. Carbohydr. Res. 148:71.

PATYKOWSKI, J., URBANEK, H., and KACZOROWSKA, T. 1988. Peroxidase activity in leaves in wheat cultivars differing in resistance to *Erysiphe graminis* D.C. J. Phytopathol. 122:126.

RACZYŃSKA-BOJANOWSKA, K., RAKOWSKA, M., BOROS, D., and ZELSKA, B. 1983. Secondary metabolism of rye grain and formation of antinutritive compounds for animals. Nutr. Rep. Int. 27:387.

RACZYŃSKA-BOJANOWSKA, K., RAKOWSKA, M., SITARSKI, J., RYBKA, K., ZEBALSKA, M., and CYRAN, M. 1989. The soluble non-digestible compounds as an index in rye breeding for better protein digestibility. J. Cereal Sci. 9:71.

RAKOWSKA, M., RACZYŃSKA-BOJANOWSKA, K., MACEWICZ, J., KUPIEC, R., and DUMA, Z. 1989. Non-digestible soluble compounds and grain structure of rye and wheat. J. Cereal Sci. 9:159.

RAKOWSKA, M., KUPIEC, R., and RYBKA, K. In press. Studies on the antinutritive compounds in rye. VI. Effect of dietary fiber fractions on protein digestibility in rats. Pol. J. Food Nutr.

RANDERATH, K. 1971. Chromatographishe sur Couches Minces, 2nd ed. Gauthiers-Villard: Paris. p. 397.

RYBKA, K., BOROS, D., and RACZYŃSKA-BOJANOWSKA, K. 1992. Comparative studies on the components of cereal grains that are indigestible in vitro. J. Cereal Sci. 15:295.

SCALBERT, A., MONTIES, B., LALLEMAND, J.-Y., and GUITET, E. 1985. Ether linkage between phenolic acid and lignin fractions from wheat straw. Phytochemistry 24:1359.

SMITH, M. M., and HARTLEY, R. D. 1983. Occurrence and nature of ferulic acid substitution of cell wall polysaccharides in graminaceous plants. Carbohydr. Res. 118:65.

SOSULSKI, F., KRYGIER, K., and HOGGE, L. 1982. Free esterified and insoluble-bound phenolic acids. 3. Composition of phenolic acids in cereal and potato flours. J. Agric. Food Chem. 30:337.

STRACK, D., ENGEL, U., WEISSENBOCK, G., GROTJAHN, L., and WRAY, V. 1986. Ferulic acid esters of sugar carboxylic acids from primary leaves of rye (*Secale cereale*). Phytochemistry 25:2605.

VAN SUMERE, C. F., De POOTER, H., ALI, H., and DEGRAUW-VAN BUSSEL, M. 1973. *N*-Feryloylglycine-L-phenylalanine: A sequence in barley proteins. Phytochemistry 12:407.

[Received August 28, 1991. Revision received May 26, 1992. Accepted May 28, 1992.]

Flow Behavior of Wheat Flour-Water Dough Using a Capillary Rheometer. I. Effect of Capillary Geometry[1,2]

N. SHARMA, M. A. HANNA, and Y. R. CHEN[3]

ABSTRACT

Cereal Chem. 70(1):59-63

A capillary extrusion rheometer was employed for detailed investigation of the flow behavior of wheat flour-water dough. Dough was extruded at ambient conditions through capillaries of different lengths and diameters. In the shear rate range of 9–5,000 sec^{-1}, the dough exhibited shear thinning with an average flow behavior index of 0.34 and consistency coefficient of 2,395 Pa-$sec^{0.34}$. The flow curves, corrected for end effects and for effect of die diameter on shear rates, were independent of capillary dimensions. The capillary rheometer technique was found to be a reliable and repeatable method for determining flow parameters of viscous materials such as dough.

As with most foods, rheological properties are important in breadmaking. The final quality of the bread can be related to the rheological properties of its flour dough, which explains the amount of research being conducted in this area. Researchers have addressed different aspects of dough rheology and have described the methods used to evaluate the rheological properties (Bloksma 1975; Hibberd and Parker 1975; Matsumoto et al 1975; Matsuo and Irvine 1975; Rasper 1975; Bushuk 1985; Dick 1985; Faubion et al 1985; Hoseney 1985; Nagao 1985; Dreese et al 1988a,b; Fitzgerald et al 1988; Refai et al 1988). Their work concentrated on the qualitative evaluation of flours. Instruments such as the farinograph or mixograph were used to obtain optimum mix time and absorption data. These instruments provide useful information about dough, but they cannot generate numerical data to characterize flow behavior. In automated bakeries, knowledge of dough viscosity plays an important role in production control and equipment design. Dough viscosity may relate to the quality of the baked product and may control that quality in some instances. On-line methods to sense dough consistency require knowledge of dough flow behavior over a wide range of flow conditions. Dough can be pumped from the point of mixing to the fermentation chamber and then to the oven, but suitable pumps cannot be designed or specified unless the dough's rheological parameters and flow behavior properties are known. None of the studies referenced above give the basic information on flow behavior needed for engineering design. Basic information on flow behavior of wheat flour-water dough based on a capillary extrusion rheometer was reported by Sharma et al (1990). They found it was possible to describe the flow behavior of dough using the capillary rheometer results. Because only one size capillary (3.21 mm diameter) with different lengths was used, the reliability of the technique needs verification at other capillary diameters. Therefore, this study was undertaken to investigate the effects of capillary geometry on the flow behavior of wheat flour-water dough.

---

[1] Published as journal series 9881, Agricultural Research Division, University of Nebraska.

[2] Use of a company or product name by the U.S. Department of Agriculture does not imply approval or recommendation of the product to the exclusion of others that may also be suitable.

[3] Packaging engineer, Westreco, Inc., St. Joseph, MO; professor, Biological Systems Engineering, University of Nebraska, Lincoln; research leader, USDA-ARS, Beltsville, MD, respectively.

MATERIALS AND METHODS

Rheometer

The capillary extrusion rheometer consisted of a cylinder-piston arrangement (Sharma and Hanna 1992). The stainless steel cylinder had an inside diameter of 37 mm and a wall thickness of 17 mm. A close-fitting plunger was constructed from a solid brass rod. The working length of the plunger was the same as the 100-mm height of the cylinder. One end of the plunger had a threaded portion that could be screwed into a coupler, which, in turn, was screwed to the cross-head of a Universal Testing Machine (UTM) (model 1123, Instron Corp., Canton, MA). The capillaries were hollow brass tubes. One end of each tube was soldered to a threaded stainless steel section that could be screwed into the threaded hole at the bottom of the cylinder's supporting collar to be flush with the inside surface. The inside diameter of the stainless steel supporting collar was slightly bigger than the outside diameter of the cylinder. The height of the supporting collar was 56 mm to avoid buckling due to excessive pressure exerted on the cylinder side walls. Three set screws were used to secure the cylinder in the supporting collar. The supporting collar was held vertically on a flat plate and the entire assembly was supported by a heavy steel stand. The complete unit was positioned under the cross-head of the UTM so that the brass plunger would smoothly slide down inside the cylinder containing the dough and force-extrude the dough through the various capillary sizes.

Dough Preparation

Bakery flour was obtained from ConAgra (Omaha, NE). The moisture content of flour was determined to be 12.6% on a wet basis (method 44-15A, AACC 1983) of drying 3 g of flour at 130°C for 1 hr in a convection oven. Bakery flour was tested in a 10-g mixograph for optimum mix time and absorption. These were found to be 3 min and 64.5 g of H_2O per 100 g of flour (on a 14% absorption basis), respectively. Subsequently, larger quantities of dough were made by mixing 100 g of flour with 64.5 g of distilled water for 3 min in a pin mixer (National Manufacturing Co., Lincoln, NE).

Rheometer Operation

The inside wall of the cylinder was lightly lubricated with corn oil. Small pieces of dough were placed in the cylinder and pushed down using a wooden rod. When the cylinder was completely filled, a lightly lubricated plastic sheet was placed on top of the sample and hand-pressed to squeeze out the excess dough and to level the dough surface. A capillary tube of known dimensions was then screwed in place. Different lengths of capillary tubes with inside diameters of 3.2, 4.0, and 5.6 mm were used to achieve various combinations of length-to-diameter ratios (L/D ratio). These ratios are given in Table I. Each capillary was first used at its maximum length. After ensuring that sufficient data were collected using one length, the capillary tubes were cut to obtain shorter lengths.

After the cylinder was placed inside the supporting collar and secured, the whole assembly was placed under the cross-head of the Instron, to which the brass plunger had already been attached. The plunger was moved down at preselected speeds of 5, 10, 20, 50, 100, and 500 mm/min to extrude the dough through the capillary tube. The extruded dough was collected in a petri dish on a Mettler PJ 3000 (Mettler Inst. Corp., Hightstown, NJ) balance that was interfaced with a personal computer for continuous recording of mass flow rate. Details of instrumentation are presented in Sharma (1990).

TABLE I
Length-Diameter Ratios for Various Capillaries

Length (mm)	Diameter, mm		
	3.2	4.0	5.7
49.7	15.5	12.3	8.9
82.2	25.6	20.4	14.7
126.2	39.3	31.3	22.5
151.5	47.2	37.6	27.3

The force required to extrude the dough was sensed by a force transducer mounted over the brass plunger and continuously recorded on the UTM strip chart recorder.

Dough density was determined by weighing a known volume of dough. Mass flow rate recorded by computer was converted to volumetric flow rate by dividing by density. Volumetric flow rate was also calculated theoretically using the plunger cross-sectional area and plunger speed.

Shear Stress and Shear Rate Determination

Wall shear stress was calculated as

$$\tau = \Delta Pr/2L ,$$

where τ = shear stress (Pa), ΔP = pressure drop across the capillary (Pa), r = radius of capillary (m), and L = length of capillary (m).

The pressure data were obtained by dividing the force recorded on the strip chart recorder by the cross-sectional area of the plunger. Total pressures were obtained for all combinations of L/D ratios. The total pressure was plotted against the ratio at each of the selected plunger speeds. Linear extrapolation was used to determine the pressure drop due to the sudden contraction, the pressure drop at L/D = 0 (Bagley 1957). The corrected pressure drop across the capillary was obtained by subtracting the entrance pressure drop due to the sudden contraction at the entrance to the capillary from the total pressure.

The apparent shear rate was calculated as

$$\dot{\gamma} = 4Q/\pi r^3 ,$$

where $\dot{\gamma}$ = shear rate (sec^{-1}), Q = volumetric flow rate (m^3/sec), and r = radius of capillary used (m). The Rabinowitsch correction was applied to obtain the corrected shear rates. The correction factor was calculated from the slope of a plot of log shear rate versus log shear stress. The slope b of the resulting straight line was used to calculate the correction factor using the formula

$$F_c = 0.75 + 0.25b ,$$

where F_c = correction factor and b = slope. The corrected shear rate was then obtained by multiplying the calculated apparent shear rate by the correction factor.

Two replications were made at each plunger speed (six), capillary diameter (three), and L/D ratio (four). The dough was extruded at an ambient temperature of 21°C. Analysis of variance was used to test the effects of capillary length and diameter on the flow parameters using a completely randomized design with a two-factor factorial treatment design.

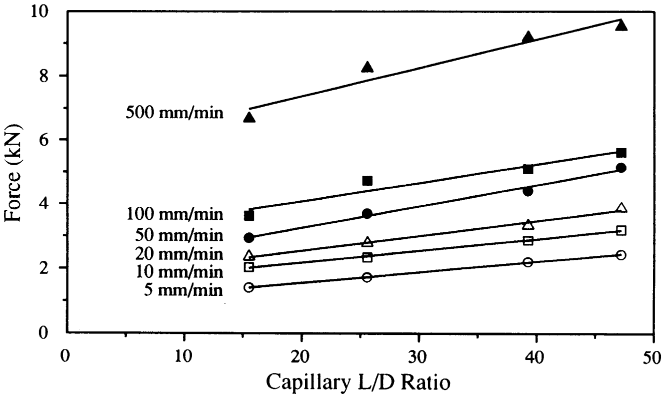

Fig. 1. Determination of entrance force drop for a 3.2 mm diameter capillary.

TABLE II
Regression Constants for the Plunger Force Equation, $F = a + b(L/D)$

Plunger Speed (mm/min)	Capillary Diameter, mm								
	3.2			4.0			5.6		
	a^a	b	R^2	a^a	b	R^2	a^a	b	R^2
5	899	33	0.999	819	18	0.940	380	17	0.960
10	1,432	37	0.997	883	30	0.972	443	24	0.949
20	1,609	46	0.988	1,440	31	0.991	507	38	0.969
50	1,902	67	0.989	1,595	51	0.882	941	34	0.956
100	2,916	58	0.928	1,819	70	0.900	1,127	60	0.997
200	5,608	88	0.937	3,818	89	0.983	2,432	50	0.952

[a] These are the entrance force drops.

TABLE III
Comparison of Total Pressures[a] (kPa) at Common Length-Diameter Ratios

Plunger Speed (mm/min)	Capillary Length-Diameter Ratio								
	15.5 Capillary Diameter (mm)			25.6 Capillary Diameter (mm)			39.3 Capillary Diameter (mm)		
	3.2	4.0	5.6	3.2	4.0	5.6	3.2	4.0	5.6
5	1,240	963	564	1,520	1,123	715	1,940	1,339	919
10	1,790	1,182	715	2,060	1,448	927	2,530	1,809	1,216
20	2,080	1,685	961	2,910	1,959	1,298	2,940	2,332	1,755
50	2,580	2,092	1,288	3,260	2,544	1,589	3,890	3,157	1,997
100	3,190	2,547	1,804	4,170	3,167	2,336	4,500	4,008	3,057
500	5,880	4,559	2,813	7,270	5,347	3,256	8,760	6,416	3,857

[a] Pressures were obtained by dividing the forces by the cross sectional area of plunger.

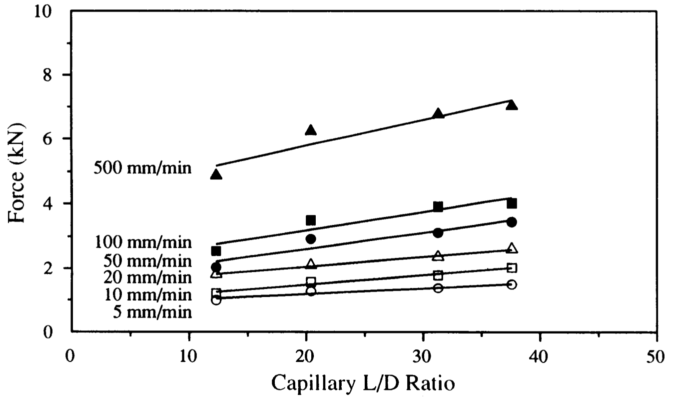

Fig. 2. Determination of entrance force drop for a 4.0 mm diameter capillary.

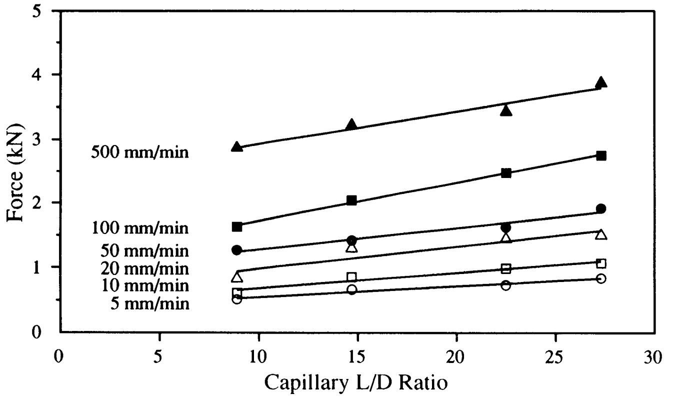

Fig. 3. Determination of entrance force pressure drop for a 5.6 mm diameter capillary.

RESULTS AND DISCUSSION

The plots of total plunger force, as recorded on the strip chart, versus the L/D ratios for the diameters tested are shown in Figures 1–3. The regression constants for the straight line relationships between total force and L/D ratio are presented in Table II.

TABLE IV
Pressure Drops (kPa) Across the 3.2 mm Diameter Capillary

Plunger Speed (mm/min)	Shear Rate ($\sec^{-1}$)	Capillary Length-Diameter Ratio			
		15.5	25.6	39.3	47.2
5	29	450	730	1,150	1,350
10	59	530	800	1,270	1,550
20	117	650	1,480	1,510	1,980
50	293	900	1,580	2,210	2,860
100	586	620	1,600	1,930	2,390
500	2,930	1,780	3,170	4,640	4,300

TABLE V
Pressure Drops (kPa) Across the 4.0 mm Diameter Capillary

Plunger Speed (mm/min)	Shear Rate ($\sec^{-1}$)	Capillary Length-Diameter Ratio			
		12.3	20.4	31.3	37.6
5	15	160	400	500	600
20	59	580	1,100	1,380	1,290
50	148	630	1,420	1,810	1,880
100	296	740	1,590	2,080	2,040
500	1,480	1,020	2,230	2,880	2,920

Because there was no common ratio within the diameters of the three capillaries used, the regression constants of Table II were used to obtain the total pressures for L/D ratios of 15.5, 25.6, and 39.3 for all capillary diameters (Table III).

Table III reflects the fact that the pressure should decrease with increasing capillary diameter at any given plunger speed. Increasing the capillary length (higher L/D ratio) would result in an increase in total pressure. As with any non-Newtonian shear thinning material, at any given capillary tube radius and specified shear, the pressure increased with increasing length of the capillary tube for the dough system tested. Both shear rate and extrusion pressure increased with increasing plunger speeds. Because pressure is proportional to Q^n (where Q is volumetric flow rate and n is the flow behavior index) for a non-Newtonian material, pressure increases with flow rate and the observed data confirm this relationship.

Tables IV–VI show the pressure drop across capillaries 3.2, 4.0, and 5.6 mm in diameter with different L/D ratios and plunger speeds (shear rates). Pressure drop across the capillaries increased with increasing shear rate for the same reasons as discussed above. Increasing plunger speed causes an increase in the volumetric flow rate that results in an increased shear rate.

The entrance pressure drop increased with increasing shear rates for any given capillary diameter. This observation is in agreement with the normal behavior of viscoelastic fluids, such as thermoplastics (Jasberg et al 1981).

TABLE VI

Pressure Drops (kPa) Across the 5.6 mm Diameter Capillary

Plunger Speed (mm/min)	Shear Rate (sec^{-1})	Capillary Length-Diameter Ratio			
		8.9	14.7	22.5	27.3
5	6	190	320	480	480
20	22	270	680	810	860
50	55	570	1,020	1,420	1,140
100	110	590	1,230	1,630	1,570
500	550	660	1,410	1,840	1,540

TABLE VII

Regression Constants for the Relationship Log $\dot{\gamma} = a + \log \tau$[a]

Capillary Diameter (mm)	Capillary Length-Diameter Ratio	a	b[a]	R^2
3.2	15.5	−11.10	3.27	0.998
3.2	25.6	−9.87	2.96	0.990
3.2	39.3	−10.47	3.12	0.989
3.2	47.2	−12.72	3.68	0.972
4.0	12.3	−6.74	2.23	0.922
4.0	20.4	−8.34	2.54	0.901
4.0	31.3	−8.16	2.53	0.903
4.0	37.6	−9.13	2.83	0.964
5.6	8.9	−13.26	3.80	0.923
5.6	14.7	−9.98	2.84	0.910
5.6	22.5	−10.79	3.08	0.941
5.6	27.3	−8.52	2.54	0.995

[a] b values were used to compute the correction factor.

TABLE VIII

Regression Constants for the Relationship Log $\tau = k + n \log \dot{\gamma}$

Capillary Diameter (mm)	Capillary Length-Diameter Ratio	Regression Constants		
		k	n	R^2
3.2	15.5	3.3437	0.3040	0.998
3.2	25.6	3.3339	0.3234	0.942
3.2	39.3	3.3090	0.3041	0.938
3.2	47.2	3.2739	0.3317	0.981
4.0	12.3	3.6726	0.2370	0.914
4.0	20.4	3.3278	0.3472	0.894
4.0	31.3	3.2912	0.3424	0.892
4.0	37.6	3.2081	0.3431	0.932
5.6	8.9	3.3489	0.4058	0.998
5.6	14.7	3.4404	0.4586	0.868
5.6	22.5	3.4934	0.3115	0.902
5.6	27.3	3.2918	0.3946	0.996

The plots of logarithmic shear rates versus the logarithmic shear stresses were linear for all capillaries. The linear regression constants were used in determining the Rabinowitsch correction factor for shear rate.

The shear stress and the corrected shear rate data (after applying the Rabinowitsch correction factor) were adequately described by the power model as seen in the regression constants in Tables VII and VIII. The values of *m* (consistency coefficient) in Table IX were obtained by taking the antilogarithm of the intercept terms, k in Table VIII. The values of *n* in Table VIII are the flow behavior indices of the dough. Analysis of variance showed that neither capillary length nor diameter had a significant effect on the flow behavior index or the consistency coefficient. The average flow behavior index was calculated to be 0.34 with a standard deviation of 0.06, and the average consistency coefficient for the dough was 2,395 Pa-sec$^{0.34}$ with a standard deviation of 829 Pa-sec$^{0.34}$. Comparison with m = 6.5 Pa-sec^{n} for a banana puree (Heldman and Singh 1981) gives relative information about the degree of dough viscosity. A value of 0.34 for the flow behavior index is indicative of the pseudoplastic nature (shear thinning) of wheat flour-water dough. Looking at the individual numbers for both flow behavior indices (*n*) and consistency coefficients (*m*) in Table IX, it was concluded, in general, that the flow curves, corrected for end effects and for effect of die diameter on shear rate, were not affected by capillary dimensions. Because only one dough composition was used for all extrusions, consistency coefficients (Table IX) are expected to be within reasonable experimental error. While we feel that the capillary extrusion technique can be used as a reliable method to obtain flow behavior data of a viscous mass such as dough, more investigation is warranted.

CONCLUSIONS

Based on the findings of this study, the following conclusions can be drawn:

1. The capillary length and diameter did not significantly affect the flow curves of the wheat flour-water doughs.
2. The capillary rheometer technique gave reproducible results and can be used for flow characterization of flour-water doughs.
3. The wheat flour-water dough was highly non-Newtonian pseudoplastic material with an average flow behavior index of 0.34 and an average consistency coefficient of 2,395 Pa-sec$^{0.34}$ in the shear rate range of 9–5,000 sec^{-1}.
4. More information should be generated to make the capillary technique acceptable for investigating dough flow behavior.

ACKNOWLEDGMENT

We gratefully acknowledge the permission granted by Michael Bagby, formerly assistant professor, College of Dentistry, University of Nebraska, Lincoln, to use his facility for conducting the experiments.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC, 8th ed. Method 44-15A, approved October 1975, revised October 1981. The Association: St. Paul, MN.

BAGLEY, E. B. 1957. End correction in capillary flow of polyethylene. J. Appl. Phys. 28:624-627.

TABLE IX

Flow Behavior Indices (n)[a] and Consistency Coefficients (m)[a] for the Bakery Flour-Water Doughs

Capillary Diameter, mm								
3.2			4.0			5.6		
L/D[b]	n	m[c]	L/D	n	m	L/D	n	m
15.5	0.340	2,206	12.3	0.2370	4,705	8.9	0.4058	2,233
25.6	0.3234	2,157	20.4	0.3472	2,127	14.7	0.4586	2,757
39.3	0.3041	2,037	31.3	0.3424	1,955	22.5	0.3115	3,115
47.2	0.3317	1,879	37.6	0.3431	1,615	27.3	0.3946	1,958

[a] Each number is an average of two observations.

[b] Length-diameter ratio.

[c] The consistency coefficients m are the antilogarithms of the intercept term k in Table VIII.

BLOKSMA, A. H. 1975. Thiol and disulfide groups in dough rheology. Cereal Chem. 52:170r-183r.
BUSHUK, W. 1985. Rheology: Theory and application to wheat flour doughs. Pages 1-26 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
DICK, J. W. 1985. Rheology of durum. Pages 219-240 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
DREESE, P. C., FAUBION, J. M., and HOSENEY, R. C. 1988a. Dynamic rheological properties of flour, gluten, and gluten-starch doughs. I. Temperature-dependent changes during heating. Cereal Chem. 65:348-353.
DREESE, P. C., FAUBION, J. M., and HOSENEY, R. C. 1988b. Dynamic rheological properties of flour, gluten, and gluten-starch doughs. II. Effect of various processing and ingredient changes. Cereal Chem. 65:354-359.
FAUBION, J. M., DREESE, P. C., and DIEHL, K. C. 1985. Dynamic rheological testing of wheat flour doughs. Pages 91-116 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
FITZGERALD, J. V., MATUSIK F. J., and WALSH, T. M. 1988. New method and instrument for rheology of dough. Cereal Foods World 33:908-912.
HELDMAN, D. R., and SINGH, R. P. 1981. Food Process Engineering, 2nd ed. AVI Publishing Co.: Westport, CT.
HIBBERD, G. E., and PARKER, N. S. 1975. Measurement of the fundamental rheological properties of wheat flour doughs. Cereal Chem. 52:1r-23r.
HOSENEY, R. C. 1985. Rheology of fermenting dough. Pages 177-191 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
JASBERG, B. K., MUSTAKAS, G. C., and BAGLEY, E. B. 1981. Effect of extruder retention time of capillary flow of soy dough. J. Food Process Eng. 5:43-56.
MATSUO, R. R., and IRVINE, G. N. 1975. Rheology of durum wheat products. Cereal Chem. 52:131r-135r.
MATSUMOTO, H., NISHIYAMA, J., MITA, T., and KUNINORI, T. 1975. Rheology of fermenting dough. Cereal Chem. 52:82r-88r.
NAGAO, S. 1985. Do-corder and its application in dough rheology. Pages 75-90 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN
RASPER, V. F. 1975. Dough rheology at large deformations in simple tensile mode. Cereal Chem. 52:24r-41r.
REFAI, A. C., FAUBION, J. M., and HOSENEY, R. C. 1988. Lubricated uniaxial compression of fermenting doughs. Cereal Chem. 65:401-403.
SHARMA, N. 1990. Modeling flow behavior of flour-water doughs. Ph.D. dissertation. University of Nebraska: Lincoln.
SHARMA, N., HANNA, M. A., and FRIESEN, B. A. 1990. Monitoring dough flow rate using a computer. Cereal Foods World 35:550-552.
SHARMA, N., and HANNA, M. A. 1992. Assessing handling properties from flow parameters as influenced by dough water content. Cereal Foods World 37:27-29.

[Received April 9, 1992. Accepted July 22, 1992.]

Flow Behavior of Wheat Flour-Water Dough Using a Capillary Rheometer. II. Effects of Water, Protein, Mix, and Rest Time[1,2]

N. SHARMA, M. A. HANNA, and D. B. MARX[3]

ABSTRACT

Cereal Chem. 70(1):63-67

Doughs made with various combinations of water, protein, and mix and rest times were extruded at ambient temperature through a capillary of known geometry. The flow behavior of the doughs was described by a power law model. The consistency coefficient decreased with increasing water content in the doughs, but it increased with increasing protein content. Mix and rest times did not show a significant effect on the consistency coefficient. The flow behavior indices were not affected by water, protein, mix time, or rest time over the ranges studied. The consistency coefficients were predicted within reasonable accuracy by a quadratic model including only water and protein as independent variables. The quantification of flow properties could be used for quality control using automated process control in bakeries of the future.

The best known application of dough rheology is in determining the baking quality of flour (Muller 1968). Quality of the finished product is thought to be largely dependent on dough rheology. This has led researchers to investigate rheological properties of doughs in detail and to report the outcomes in a large number of publications (Udy 1953, Dempster and Hlynka 1958, Bayfield and Stone 1960, Glucklich and Shelef 1962, Hlynka 1962, Bloksma 1968, Funt et al 1968, Lerchenthal and Funt 1968, Navickis et al 1982, Faubion et al 1985, Abdelrahman and Spies 1986, Dreese et al 1988, Refai et al 1988, and Preston 1989). These studies evaluated the effect of mixing time, temperature, water, and several additives on the storage modulus, loss modulus, loss tangent, elasticity, and plasticity of doughs. In general, these studies were related to quality of flour and dough performance in baking, but the information cannot be applied to engineering calculations. In automated bakeries of the future, it is envisioned that the use of off-line or laboratory instrumentation will not be possible (Faubion and Faridi 1986). Rather, on-line sensors will assess the difference in the dough's mechanical properties, and a control system will order the necessary adjustments. Flour uniformity, dough consistency, and flow properties of dough are the characteristics that appear to be important for designing automatic control systems for the bakeries of the future. At present, not much information is available on the flow behavior of dough. Some literature exists on flow characteristics of flour-water and other food suspensions (Kitterman and Rubenthaler 1971, Doublier 1981, Doublier et al 1987, Vergnes and Villemarie 1987, Alloncle et al 1989, Steffe et al 1989), but the information is not applicable to doughs. Sharma (1990) studied flow characterization of dough itself, as opposed to flour-water suspensions, using the capillary technique, which proved to be successful in handling highly viscous doughs. The flow behavior of flour-water dough with a fixed composition (fixed amount of water and flour) was described. In reality, doughs can be made from flours with varying amounts of proteins, and with different amounts of water, depending on the desired final characteristics of the finished product. It is important to know how the flow behavior is affected by changes in water or protein content. Therefore, this study evaluated the effects of changing water content

---

[1] Published as journal series 9882, Agricultural Research Division, University of Nebraska.

[2] Use of a company or product name by the U.S. Department of Agriculture does not imply approval or recommendation of the product to the exclusion of others that may also be suitable.

[3] D. B. Marx, professor, Biometry, University of Nebraska, Lincoln.