Study of the Rheological Behavior of Corn Dough Using the Farinograph

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ABSTRACT

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An expression for power consumption in the farinograph, considered as a mixer, was used to calculate indices of apparent viscosity and to study the rheological behavior of corn dough. The results indicated that freshly prepared corn dough (65–70% moisture) behaves as a pseudoplastic fluid. In contrast to the behavior of common fluid foods, the viscosity of corn dough (prepared from commercial, Venezuelan, precooked corn flour) increased with increasing mixing temperature, possibly a result of effects of heat on the dough components. The results showed that the farinograph can be used to gain an insight into corn dough rheology.

In Venezuela and other Latin American countries, corn is used to prepare *arepas* (South America) and *tortillas* (Mexico and Central America). Several quality and process control technologies have been adapted by the corn industry from the wheat industry. The farinograph is an instrument frequently used for corn dough characterization, but no more than the conventional farinogram interpretation is usually obtained. However, modern mechanization of processes for handling corn dough, or product development studies, could use data on the rheological parameters or behavior of the dough.

The farinograph is defined as a torque-measuring-recording dough mixer. According to Shuey (1972), the farinograph measures "... the plasticity and mobility of a dough subjected to a prolonged, relatively gentle mixing action at a constant temperature." Therefore, the torque applied during mixing of a doughlike material may be recorded as a function of mixing time. Information about optimum mixing time, dough stability, etc., may be obtained from the apparatus. Nevertheless, the tests usually performed in the farinograph are empirical, and aside from comparative tests the farinograph is not suitable for deeper studies on dough rheology (Shuey 1972, Rasper 1976).

Some investigators (Bayfield and Stone 1960, Hlynka 1962) have used the farinograph for studying the effect of temperature and speed of mixing on some rheological properties of wheat dough. In the present study it was postulated that some insight into the rheology of corn dough could be obtained from a fluid dynamics analysis of the farinograph considered as a mixer. We present here an adaptation and application of this approach (using well-known fluid dynamics equations for mixing systems) to the study of the rheological characteristics of corn dough as a function of concentration, temperature, and speed of mixing.

The factors that affect the agitation and mixing of a liquid or a paste are the apparent viscosity (μ_{app}) and the density (ρ) of the material, the speed of rotation (N) of the agitator or mixer, the acceleration of gravity (if a vortex is formed during agitation), and the geometric or shape factors ($S_1, S_2, \ldots, S_n$). The power (P) required to rotate a given agitator with diameter D_a at a given speed, is a function of those factors. According to the reasoning of McCabe and Smith (1976), this function may be expressed as:

$$P = f(N, \mu_{app}, \rho, g, S_1, S_2, \ldots, S_n). \tag{1}$$

Application of dimensional analysis in a conventional way gives (McCabe and Smith 1976, Bird et al 1960, Charm 1978):

$$\frac{P g_c}{N^3 D_a^5 \rho} = f\left(\frac{N D_a^2 \rho}{\mu_{app}}, \frac{N^2 D_a}{g}, S_1, S_2, \ldots, S_n\right), \tag{2}$$

where the dimensionless group on the left is the power number N_P (or drag coefficient for mixing); the first group on the right is the Reynolds number for mixing N_{Re}; the second group is the Froude number N_{Fr}; the shape factors $S_1, S_2, \ldots, S_n$ are ratios of the system dimensions; and g_c is Newton's law constant (which may or may not be included, depending on the system of units used).

The effect of the Froude number is important when there is vortex formation, for large N_{Re} (usually for $N_{Re} > 300$). In the farinograph, $D_a = 0.03695$ m, and the maximum speed available is 200 rpm. If we take a density of 1,110 kg/m^3 for corn dough and an apparent viscosity (as an extreme case for high shear rates) of 30 Pa·s (*unpublished data*), $N_{Fr} = 0.042$, and $N_{Re} = 0.17$; therefore, the Froude number can be neglected, and the Reynolds number indicates laminar flow. If the viscosity falls (due to higher shear rates), for example, to 10 Pa·s, N_{Re} would be 0.5, which still would be a very low value. Because the Froude number is not important, equation 2 becomes:

$$\frac{P g_c}{N^3 D_a^5 \rho} = f_1\left(\frac{N D_a^2 \rho}{\mu_{app}}, S_1, S_2, \ldots, S_n\right), \tag{3}$$

or

$$N_P = f_1(N_{Re}, S_1, S_2, \ldots, S_n). \tag{4}$$

Using the energy equation for analyzing agitation power

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requirements in a mixer would lead to an expression equivalent to equations 3 and 4, relating the force applied to the fluid per unit area or power input (in the power number) to the Reynolds number. The shape factors can be accounted for by a constant for a given mixer and agitator geometry (McCabe and Smith 1976). If the shape factors are expressed as the function $f_2 = f_1(S_1, S_2, \ldots, S_n)$ valid for the farinograph used, and because the power applied to the agitator shaft is given by $P = T\,N$ (where T is the torque), equation 3 or 4 becomes:

$$\frac{T g_c}{N^2 D_a^5 \rho} = f_1 f_2 \left(\frac{N D_a^2 \rho}{\mu_{app}}\right). \tag{5}$$

MATERIALS AND METHODS

Determination of the Function in Equation 5

Water was added to commercial rice syrup (84° Brix) obtained by acid hydrolysis (Favepro, Barquisimeto, Edo. Lara, Venezuela) to make diluted syrups (74, 75, 76, 78, 80, and 82° Brix). The viscosities of these syrups were measured (at 23° C) in a Brookfield viscosimeter (model RVT) using spindle no. 5; the readings were taken after 1 min of rotation at each speed (between 0.5 and 50 rpm). The density of the syrups was determined (at 23° C) by weighing a previously tared, graduated cylinder containing 50 ml of syrup. The Brabender consistency of the syrups (in Brabender Units, BU) was determined by placing 125 ml of syrup in the small bowl of the farinograph (model FA-MV100). The mixer and syrup temperatures were kept at 23° C using a constant temperature bath (Brabender Thermotron type 100R). The syrup was then agitated at a given speed (60, 90, or 120 rpm) for a standard time (10 min), using a lever system ratio of 1:1. The consistency of the syrup was taken as the maximum value in the stabilized farinographic curve. All measurements were made by at least real duplicates, following a completely randomized design.

In the farinograph, the mixing speed (N) is measured in rpm. Therefore, a correction has to be made for using the equations, in which N is in revolutions per second. The farinogram scale goes from 0 to 1,000 BU, which with lever position 1:1 corresponds to a torque from 0–200 gf·m. Therefore, the y-axis reading (consistency in BU) multiplied by 0.0002 gives the torque T in kgf·m. The sigma agitator diameter is $D_a = 0.03695$ m, and $g_c = 9.8\ \mathrm{kg \cdot m / kgf \cdot s^2}$.

The physical characteristics and speed of the farinograph, and the properties of the syrups (Brabender consistency, Brookfield viscosity, and density), were used to calculate the power number (N_P) and the Reynolds number (N_{Re}). The function in equation 5 was determined by regressing log N_P against log N_{Re}.

Determination of Corn Dough Consistency

Commercial, precooked corn flour (Promasa, Chivacoa, Yaracuy, Venezuela) was used to prepare the dough by placing a given amount of flour in a beaker, adding the appropriate amount of water at the test temperature, and stirring vigorously with a glass rod for 1 min. One hundred grams of the dough was quickly transferred to the small bowl of the farinograph, which was kept at a constant temperature as described for the rice syrups. Once the dough was in the bowl, it was mixed for 10 min at a fixed speed, with the torque lever in the 1:1 position.

The tests were performed according to a completely randomized design, in a 3×3×2 factorial arrangement replicated twice, in which the independent variables were temperature (t), mixing speed (N), and composition (c), respectively. The dependent variable was consistency, expressed in BU. The levels of the variables were: temperature 30, 50, and 70° C; mixing speed 60, 90, and 120 rpm; and composition 35 and 40% flour in the dough. The dough with 35% flour was called the 65/35 dough, and the one with 40% flour was called the 60/40 dough. The latter is a dough suitable for Venezuelan *arepa* preparation.

RESULTS AND DISCUSSION

Relationship Between Power Number and Reynolds Number

A plot of N_P as a function of N_{Re} is shown in Figure 1. Data on density, Brookfield viscosity, and Brabender consistency of rice syrups, for various concentrations and mixing speeds (at 23° C) demonstrate that in the farinograph, at low Reynolds numbers, the power number, N_P, is related to the Reynolds number (within experimental error range), as is the case for several agitator geometries (McCabe and Smith 1976). Based on the regression equation (Fig. 1), and after some rearrangement, equation 5 becomes:

$$\mu_{app} = \frac{T g_c}{K N D_a^3}, \tag{6}$$

where K is the constant relating the power number (or drag coefficient for the agitation system) to the Reynolds number in the low N_{Re} region. The value of K, obtained using regression analysis, is K = 161.4 for these experiments.

In equations 1–6, μ_{app} is the average apparent viscosity, which is a function of an average velocity gradient (shear rate) in the mixing system (McCabe and Smith 1976). In the farinograph and from the foregoing analysis, once K is known, equation 6 may be used for obtaining a relative indicator, that is, an index of the viscosity of a paste or dough, from the farinographic curves and for the shear rate range (unknown) obtained in the apparatus. As in texture measurements (Bourne et al 1966, Bourne 1968), the peak value for the response may be related to the maximum energy input from the instrument to the material being tested. Thus, the maximum farinographic consistency (in BU) may be related to the maximum index of apparent viscosity of a given dough, under the specific testing conditions being used.

Table I presents data on densities and Brookfield viscosities of rice syrup at several concentrations. Although a small effect of spindle speed on viscosity was noticed for the more concentrated syrups (80 and 82° Brix), this effect did not influence the linearity of the regression shown in Figure 1, and therefore it was neglected when calculating N_{Re} and K. The analysis of variance for the Brabender consistency of the rice syrups and a coefficient of variation of 5.52% indicated that variability in the experimental data is small.

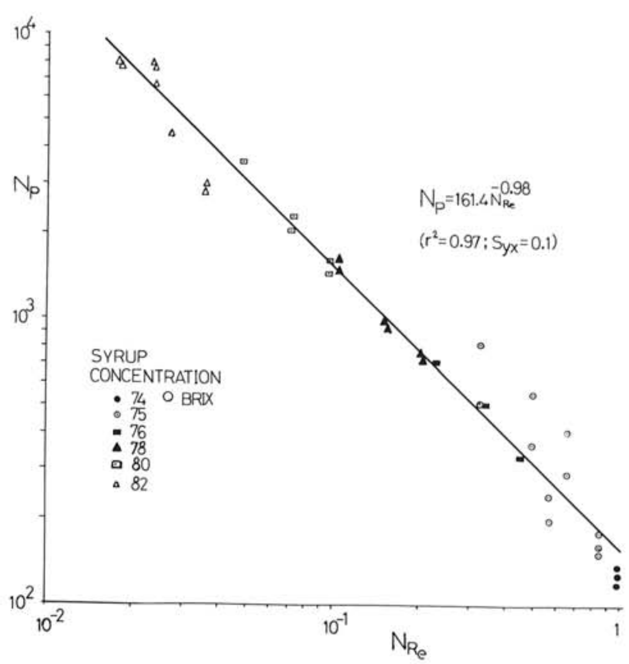

Fig. 1. Power number as a function of Reynolds number for rice syrups.

Rheological Properties of Corn Dough

The maximum consistency (in BU) attained by the dough upon mixing was read from the farinograms and is presented in Table II for the 60/40 dough and in Table III for the 65/35 dough. Both tables show that the result of mixing at a higher speed was a higher dough consistency. The data in Tables II and III followed the behavior suggested by equation 6, namely, that torque is proportional to mixing speed. The apparent viscosity index data of the dough are also shown in Tables II and III. The index of viscosity decreased when mixing speed increased. The results corresponded to a property of the dough (index of apparent viscosity) as opposed to a measurement of the mixing apparatus (the torque developed when the fluid is agitated). Hence, the results presented in Tables II and III indicated a real trend in the rheological behavior of corn dough; and therefore, it may be said that corn dough is a non-Newtonian fluid of the pseudoplastic type when prepared and tested as indicated in this work. This agrees with the results presented by Harper (1981) for corn dough at elevated temperatures, and by Lancaster et al (1966) and Evans and Haisman (1979) for corn starch suspensions and pastes.

The effect of temperature on apparent viscosity of corn dough does not follow the typical trend for most liquids, namely, that viscosity should decrease with temperature. Apparently, the dough is heat-conditioned during the test (at a given temperature), and this may result in the change or rearrangement of dough components. During the tests it was noticed that the dough at 50° C was stickier than the dough at 30° C, and the dough at 70° C was the stickiest of the three. Besides the expected effects on dough viscosity that the industrial process induced in the commercial precooked corn flour (Cuevas et al 1985), the mixing and heating operations influence the viscosity of dough suspensions (Padua and Padua 1984). Viscosity values in Tables II and III were calculated using equation 6 and the value of K obtained from Figure 1 for rice syrups. The viscosity of the syrups is obviously expected to be influenced by temperature; however, this effect is incorporated into the x-axis of Figure 1 (in the Reynolds number) as well as into the y-axis, because the power imparted by the agitator to the fluid depends on a contribution of the friction force, which in turn depends on the viscosity of the fluid (Bird et al 1960). Hence, it is reasonable to expect that the value of K will remain fairly constant as mixing temperature changes.

TABLE I
Viscosity and Density of Rice Syrups[a]

Concentration (°Brix)[b]	Brookfield Viscosity (kg/m·s)	Density (kg/m^3)
74 III	2.84	1,375
75 I	5.68	1,371
75 III	3.33	1,382
76 II	8.29	1,388
78 II	18.35	1,401
80 I	40.00	1,413
82 I	108.00	1,418
82 III	123.57	1,418

[a] Average of triplicate measurements.

[b] First, second, and third set of experiments indicated by I, II, and III, respectively, corresponding to three different samples of 84° Brix syrup.

TABLE II
Brabender Consistency and Index of Apparent Viscosity of the 60/40 Corn Dough From Precooked Flour

	Mixing Speed (rpm)					
	60		90		120	
Temperature (°C)	Consistency (BU)	Viscosity Index (kg/m·s)	Consistency (BU)	Viscosity Index (kg/m·s)	Consistency (BU)	Viscosity Index (kg/m·s)
30	280	67.40	290	46.54	315	37.91
50	270	64.99	295	47.34	315	37.91
70	300	72.22	320	51.35	360	43.33

TABLE III
Brabender Consistency and Index of Apparent Viscosity of the 65/35 Corn Dough from Precooked Flour

	Mixing Speed (rpm)					
	60		90		120	
Temperature (°C)	Consistency (BU)	Viscosity Index (kg/m·s)	Consistency (BU)	Viscosity Index (kg/m·s)	Consistency (BU)	Viscosity Index (kg/m·s)
30	165	39.72	180	28.89	180	21.66
50	165	39.72	195	31.29	200	24.07
70	225	54.16	240	38.51	250	30.09

As with other food products, a more concentrated dough has a higher viscosity (Tables II and III). This is true for fluid dough, as in this work, and for semisolid dough, as Padua and Whitney (1982) have demonstrated. The effect of agitation speed on the apparent viscosity is greater for the 60/40 dough. This is logical, because as the dough becomes more concentrated it departs further from Newtonian behavior. The differences between the 60/40 and 65/35 doughs were greater at 30° C, and as temperature increased the differences between the doughs became smaller. In other studies, it has been found that water level affects the adhesiveness and hardness of *arepa* dough (Padua and Padua 1984).

The results of the analysis of variance of the Brabender consistency of corn dough indicated that all the variables (temperature, mixing speed, and concentration) had significant (5% level) effects on consistency. The coefficient of variation is 0.48%, which implies that the variation in the data is very small.

The data presented in Tables II and III have practical implications. In Venezuela the dough can be used at the home, restaurant, or industrial level, in operations such as mixing, molding, pumping, heating, etc. As an example, for *arepa* preparation in Venezuela (by hand or in molds), a certain consistency in the dough is required. Because the viscosity increases with temperature, it is convenient to use warm dough for molding operations. When precooked corn flour and water are mixed in industrial or pilot plant mixers, it is convenient to have a thin dough, so that energy and time required for mixing are small; in this case, it is desirable to operate at ambient temperature. The same is true for pumping dough. If the power required for pumping has to be calculated, the factors to be considered are that a higher shear rate will result in a lower viscosity, if the postulate that the dough is a shear thinning fluid is accepted, and this will affect the Reynolds number. Of course, an increase in velocity will also affect the Reynolds number, the friction factor, and the energy of the flowing dough.

CONCLUSIONS

In this work we have shown how farinographic data can be analyzed, considering the apparatus as a mixer, to obtain an indication of the rheological behavior of the test material. The geometric and fluid dynamics characteristics of the mixing system are expressed as a dimensionless constant (K), which has the value of 161.4 for mixing speeds between 60 and 120 rpm (small bowl, torque lever position 1:1) and for the experimental conditions used in the tests. In this way, indices of apparent viscosity of freshly prepared corn dough (from precooked corn flour) were obtained. The index of apparent viscosity increased with temperature and concentration and decreased with agitation speed (pseudoplastic behavior).

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