Transformation of Wheat Flour by Extrusion Cooking: Influence of Screw Configuration and Operating Conditions

C. BARRÈS,[1,2] B. VERGNES,[1] J. TAYEB,[3] and G. DELLA VALLE[3]

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ABSTRACT

An experimental study of wheat flour extrusion cooking was carried out on two different sizes of twin-screw extruders (Clextral BC 45 and BC 72). By stopping the machine and rapidly opening the barrel, the location of the material in the screws was observed, and samples were collected in order to analyze the macromolecular transformation of the product. This transformation was evaluated through starch solubility measurements. The influence of screw configuration and operating conditions on the level of transformation was examined. It appeared that the reverse screw element played a major role and that varying the feed rate induced more effects in terms of product transformation than varying the screw speed. Theoretical investigations of the flow through the reverse screw element were developed in order to compute the specific energy given to the material. The level of transformation appeared to correlate well with energy input. This might provide an interesting basis to solve extruder scale-up problems in extrusion cooking.

The transformation of starchy products by extrusion cooking has interested many authors for more than 10 years. It is well known now that the most important modification is a molecular degradation of starch, affecting both amylopectin and amylose components. This was demonstrated by gel permeation chromatography or intrinsic viscosity measurements for pure starches (Colonna and Mercier 1983; Colonna et al 1984; Davidson et al 1984a,b; Diosady et al 1985) and flours (Schweizer and Reimann 1986, Holm et al 1988).

The evolution of this transformation along the screw was observed when opening the barrel after a dead stop procedure on single-screw extruders (Paton et al 1980, Diosady et al 1985) and on twin-screw machines (Colonna et al 1983, Fletcher et al 1984, Senouci and Smith 1986).

It has been shown in previous work, performed on a preshearing rheometer (Vergnes et al 1987), that the macromolecular degradation of pure starch is directly connected with the mechanical energy supplied to the product by shear. Experimental relations between measured specific energy and product transformation for twin-screw extruders were reported by Meuser and Van Lengerich (1984a,b) and Della Valle et al (1989).

The purpose of this work was to develop such approaches and their theoretical background for the transformation of wheat flour under different processing conditions and on machines of two different sizes, in order to check the existence of various functional zones in the extruder (solid conveying, melting, and pumping sections) as well as the influence of screw profile and processing conditions. Variations in product transformation were also simulated by computing the specific energy provided in the reverse screw element.

Our objective was to improve the theoretical approach

[1]Centre de Mise en Forme des Matériaux, UA CNRS 1374, Ecole des Mines de Paris, Sophia Antipolis, 06560 Valbonne, France.
[2]Clextral S.A., P.O. Box 10, 42702 Firminy Cedex, France.
[3]Institut National de la Recherche Agronomique, Laboratoire de Biochimie et Technologie des Glucides, Rue de la Géraudière, 44072 Nantes Cedex 03, France.

developed by Tayeb et al (1988, 1989) in order to correlate the specific energy to the product transformation. Such a work will be useful in predicting the final properties of a product extruded under certain conditions or to define the processing conditions required to obtain a desired product.

MATERIALS AND METHODS

Materials

Two corotating twin-screw extruders were used in this study: Clextral BC 45, a pilot-scale machine (flow rates in the range of 10–90 kg/hr), and Clextral BC 72, a classical industrial one (flow rates in the range of 80–200 kg/hr) (Clextral, Firminy, France). These machines had modular barrels and the screws were composed of direct-flighted elements of decreasing pitches and reverse-flighted elements, generally situated adjacent to the die. Three slots were cut in the flights of the reverse-screw elements, parallel to the screw axis, in order to allow the material to flow forwards. The width of the axial slots was 6, 8, or 10 mm on the BC 45 and 8 or 14 mm on the BC 72.The dies used were composed of two parallel cylindrical ducts, with a diameter of 4 mm on the BC 45 and 7 mm on the BC 72. The different screw configurations tested are listed in Table I. Only the final part of the screw was modified.

In general, commercial wheat flour with 5% added water (i.e., total moisture content of 17.6%, wet basis) was used for the study. However, for the dead stop experiments, the moisture content in the wheat flour was increased to 21.4% (wet basis) in order to make the opening of the extruder barrel easier. It is clear that the difference in moisture content may affect the results and prohibits a direct comparison of experiments on final transformation (moisture content 17.6%) and the dead stop experiments (moisture content 21.4%). However, the general trends observed, as well as the respective influence of the different parameters (screw speed, feed rate, screw geometry), remained valid, whatever the moisture contents chosen.

Operation of Extruders

Rotation speed (N) and feed rate (Q) were varied respectively in the range 150–250 rpm and 10–90 kg/hr on the BC 45, and 80–230 rpm and 80–160 kg/hr on the BC 72. The feed rate was imposed by a volumetric feeder and checked by weighing the extruded product at the die exit.

In each case, after steady state flow conditions were attained, samples were collected at the die exit for further analyses. Dead stop procedures were followed for a selective number of samples in steady state conditions; feeding, screw rotation, and barrel heating were suddenly stopped and the barrel was cooled rapidly by running cold water through the cooling coils. A few minutes later, the barrel was opened using the sliding system of Clextral extruders. After observing the degree of filling of the screws and the location and physical state of the material, C-shaped samples were collected from the screws for further observation and solubility measurements. This procedure, already used by different authors (Colonna et al 1983, Fletcher et al 1984, Senouci and Smith 1986), allowed us to characterize correctly the product transformation, since the main parameter governing the macromolecular degradation is the shear (Vergnes et al 1987), which was stopped at the same time as the machine. Moreover, the opening of the barrel after dead stop took no more than 5 min. A local transformation of the product in contact with the barrel might occur during this time (leading to a light brown colored material), but, due to the very low thermal conductivity of wheat flour, this effect was limited to the surface of the sample and would not affect the global evaluation of the transformation.

TABLE I
Screw Configurations

Extruder	Screw Element Dimensions (mm) Length	Pitch[a]
BC 45[b]	200	50
	200	35
	100	15
	50	15, 15, −15
	50	15, −15, 15
BC 72[b]	400	52
	200	35
	200	28
	100	28, −28
	100	−28, 28

[a] Negative pitches represent reverse screw elements.
[b] BC 45: two cylindrical dies, 4-mm diameter; BC 72: two dies, 7-mm diameter.

Rheoplast Experiments

The preshearing rheometer Rheoplast (Villemaire and Agassant 1984) was used to simulate an extrusion treatment by supplying the wheat flour product with an equivalent thermomechanical energy. In the Rheoplast, the computation of mechanical energy was easy due to its simple geometry (coaxial cylinders) and the independence of thermomechanical variables (time, shear rate, and temperature). Moreover, it was possible to relate this parameter with the transformation of pure starch (Vergnes et al 1987). Thus, the Rheoplast was used to estimate the amount of mechanical energy necessary to obtain a certain level of wheat flour transformation. Different treatments were simulated with temperatures regulated between 110 and 170°C, rotation speeds in the range of 200–600 rpm (corresponding to shear rates in the range of 75–225/sec) and processing times varying between 10 and 60 sec.

Solubility Measurements

Due to substrate complexity, starch macromolecular state was difficult to evaluate by classical measurements such as intrinsic viscosity and had to be deduced from the analysis of functional properties. Among them, starch paste viscosity and water solubility appeared to be the most reliable as far as starch only was concerned. The studies of Colonna et al (1984), Doublier et al (1986), and Mason and Hoseney (1986) showed that hot paste viscosity was positively correlated to product intrinsic viscosity, which was found to be related to specific mechanical energy measurements (Meuser et al 1982, Della Valle et al 1989). Viscoamylograph Brabender measurements require a certain amount of product, which in our case would have been very difficult to collect from each C-shaped chamber of the screws. Water solubility measurements were therefore chosen since they permitted rapid obtainment of quantitative results with only a few grams of material, as previously shown by Meuser and Van Lengerich (1984a) or Kirby et al (1988). We followed the method of Anderson et al (1969). However, the procedure was slightly modified for wheat flour. The samples were ground in a Rousselle hammer mill (linear velocity 50 m/sec) and sieved between 125 and 250 μm. Samples of 500 mg were stirred for 60 min under maximal agitation conditions in water (1% concentration) in a thermostated bath at 30°C (Haake SWB 20). They were then centrifuged for 10 min at 10,000 rpm at 10°C. The supernatant was then titrated with orcinol in a Technicon automated spectrocolorimeter. The dry fraction of unsolubilized product (sediment) was determined from weighing the residue after desiccation for 2 hr at 130°C. Measurements on the supernatants and the residues provided results that were generally in good agreement with each other.

Theoretical Approach

Previous experimental work on similar screw profiles (Colonna et al 1983) showed that the major part of starch transformation was achieved in the reverse screw element (RSE) after the melting phase and was connected to the energy supply. Therefore, a theoretical model was developed in order to compute flows and energy inputs in the RSE.

Principles of computation. The model is a development of the previously published work of Tayeb et al (1988). The basis of this method considers a plane representation of the RSE, in which three kinds of flows might be observed: Q_D, direct flows through the axial slots; Q_R, reverse flows along the screw channel; and Q_A, reverse flows through the intermeshing zone of the screws. Assuming some restrictive hypotheses as isothermicity, Newtonian equivalent rheology of the melt, and stationary geometry, each flow rate appeared as the sum of a drag flow and a pressure flow, i.e., as a linear expression with respect to pressure gradients: $Q = \alpha + \beta\Delta P$. Coefficients α and β were dependent on geometric and rheological characteristics and on process variables (screw speed). At each node (i.e., each intersection between different flows), a balance equation was written that expressed mass conservation of the material. This resulted in a linear system with the node pressures as unknowns. Its resolution provided the pressure field in the RSE as well as flow rate distribution.

Specific mechanical energy. Power is dissipated in the RSE by viscous shearing. The volumic power was expressed as:

$$\dot{W} = \eta \cdot \dot{\bar{\gamma}}^2 \quad (1)$$

where η is the viscosity and $\dot{\bar{\gamma}}$ the generalized shear rate (i.e., including the transversal and longitudinal components of the velocity). Integrating equation (1) over the volume of each channel section (direct, reverse, intermeshing) and summing these values for all sections of the RSE provided an overall estimation of the total instantaneous power dissipated in the whole RSE, $\dot{W}_{tot}$. With V being the volume of material in the RSE (free volume between barrel and screws), ρ the density of the melt (approximately 1,500 kg/m^3), and $\bar{t}$ the mean residence time, the average specific mechanical energy received by the material flowing through the RSE was expressed as:

$$SME = \frac{\dot{W}_{tot} \cdot \bar{t}}{\rho \cdot V} \quad (2)$$

The mean residence time was defined as $\bar{t} = V/Q_v$, Q_v being the volumetric flow rate. Then, the specific mechanical energy was finally computed as:

$$SME = \dot{W}_{tot}/Q \quad (3)$$

RESULTS

Rheoplast Experiments

In the range of operating conditions listed previously, wheat flour solubilities varied between 0 and 60% (dry basis). Such values were shown to correspond to specific mechanical energy in the range of 15–600 kJ/kg (approximately 4–170 kWhr/t). For the same level of energy, the solubility of the wheat flour appeared to be much lower than that of pure maize starch (Vergnes et al 1987). For example, an energy input of 200 kJ/kg led to solubility of about 80% for maize starch and only 20% for wheat flour.

Extrusion Experiments

Product transformation. In all cases, for the materials sampled at the die exit, the solubilities varied in the range of 5 to 30% in the BC 45, and 5 to 50% in the BC 72. Similar influences of feed rate, screw speed, and degree of filling were observed with both the BC 45 and the BC 72 and with different screw profiles. Therefore, most of the results presented in this section deal with the BC 45.

An increase of feed rate (Q), for a given screw profile, induced a clear decrease in solubility of the extrudate, whereas the influence of rotation speed (N) seemed to be more moderate (Fig. 1). Feed rate (Q) and screw speed (N) can be equated through the ratio of Q/N, which is representative of the degree of filling of the screw. This ratio may be made dimensionless by dividing the feed rate (Q) by the maximum flow rate in the feeding section, i.e., $Q_{max} = \rho \cdot N \cdot B \cdot S_a$ (where ρ = density, N = screw speed, B = screw pitch, and S_a = free section between barrel and screws). The degree of filling was then defined by $\tau_r = Q/Q_{max}$ and it allowed master curves for the different experimental conditions to be generated. In our experiments, the values of the degree of filling were always limited (between 0.01 and 0.2) and, as can be seen in Figure 2, the higher the degree of filling, the lower the extrudate solubility.

The length of the RSE seemed to induce the highest variations in transformation. In Figure 2, it can be seen that using two RSEs (length of each element was 5 cm on the BC 45) led to a level of solubility that could not be reached with one or no RSE.

A comparison of the BC 45 and the BC 72 results provides a first basis for the interpolation of processing conditions (Fig. 3). For example, a 35% water solubility level could be achieved on the BC 45 at 200 rpm with a feed rate of about 27 kg/hr if using one RSE, and more than 50 kg/hr if using two RSE. For the same product in the BC 72 at 130 rpm, the feed rate could reach 80 kg/hr with one RSE and 110 kg/hr with two RSE.

As a summary of these experiments, the level of transformation of the extrudate was mainly determined by the screw geometry and the feed rate, and to a lesser degree by the rotation speed.

Transformation along the screw. The physical state and location of the material, as well as the degree of filling of the screws, were revealed by opening the barrel after a dead stop procedure.

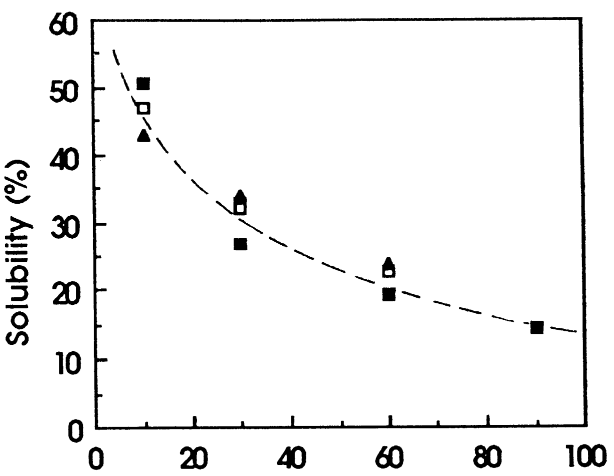

Fig. 1. Influence of feed rate and rotation speed on extrudate solubility. BC 45, one reverse screw element, 8-mm-wide slots: 250 rpm (■), 200 rpm (□), 150 rpm (▲).

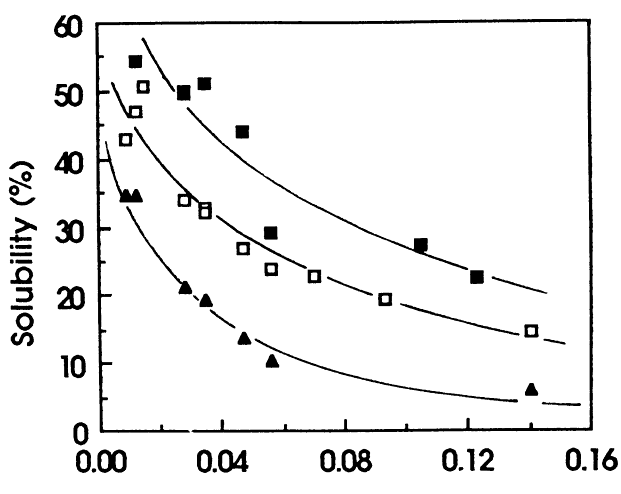

Fig. 2. Influence of degree of filling and number of reverse screw elements (RSE) on extrudate solubility. BC 45, 8-mm-wide slots: 2 RSE (■), 1 RSE (□), 0 RSE (▲).

Colonna et al (1983) reported that different zones could be observed: a solid conveying zone, where the screws were only partially filled with a white granular material; approaching a flow restriction (die, RSE), where the flour began progressively to completely fill the channels, then compacted and rapidly melted; and at the screw end, where the channels were totally filled with a molten material.

Various problems arose during these experiments. The fusion process was not instantaneous and began in contact with the flight flanks or the screw surface. This process then spread over several C-shaped chambers before all the material had melted. So, evaluation of complete melting was rather subjective, and the following schemes are only indicative of the place where the product was assumed to have totally melted. Even in the melt zone, the C-shaped samples were not completely homogeneous; thus, the way these samples were cut and ground before analysis could have interfered with the solubility results. This explains why slight differences resulting from sample heterogeneity were not considered significant and consequently not discussed.

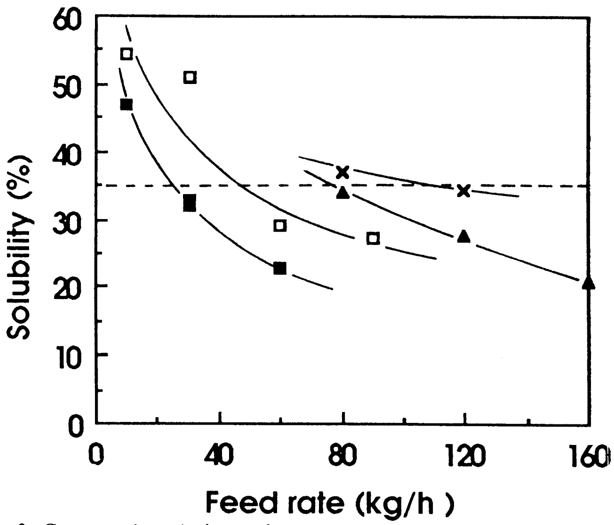

Fig. 3. Compared evolutions of extrudate solubility on BC 45 and BC 72: BC 45, one reverse screw element (RSE), 8 mm-wide slots, 200 rpm (■); BC 45, 2 RSE, 8-mm-wide slots, 200 rpm (□); BC 72, 1 RSE, 14-mm-wide slots, 130 rpm (▲); BC 72, 2 RSE, 8-mm-wide slots, 130 rpm (x).

It was observed that the evolution of solubility started in the compacted solid section (Fig. 4). This evolution was similar for both the right and the left screw, even though the degree of filling was slightly higher on the right screw than on the left one. Thus, in the following, the right screw only will be represented. The transformation of the product appeared as a progressive phenomenon, which increased gradually from the compacted solid to the melting zones and more rapidly at the entrance of the RSE.

Decreasing the rotation speed induced a higher degree of filling of the screw (Fig. 5). When dividing the rotation speed by two, the number of C-chambers filled with the melt before the RSE was doubled, and the solid conveying zone was longer, too. Due to this, transformation started earlier but increased more gradually because of the slow rotation speed. Then, the final level of degradation was not significantly different, as mentioned earlier.

As far as screw configuration was concerned, the number of RSEs played an important role (Fig. 6). With two elements, a higher filling of the screw was achieved, inducing an earlier transformation and a higher final solubility (24% instead of 19%). Conversely, the width of the axial slots was less influential. Among the range of widths tested (6- and 10-mm-wide slots), no effect could be detected either on the filling of the screw or on the solubility profiles (Fig. 7).

These results were confirmed in more severe conditions on the BC 72 at low moisture content (17.6% wet basis), with two different screw profiles—a classical one (one RSE, 14-mm-wide slots) and a more severe one (two RSE, 8-mm-wide slots). How the screw configuration affected the evolution of the product transformation under the same processing conditions (80 kg/hr, 130 rpm) can be seen in Figure 8; with the more severe configuration (two RSE, 8-mm-wide slots) the final product reached a solubility of 37% instead of 25% with the other configuration.

DISCUSSION

The evolutions of computed mean residence time ($\bar{t}$) and shear dissipated power ($\dot{W}_{tot}$) with feed rate (Q) and rotation speed (N) are plotted in Figure 9. The mean residence time ($\bar{t}$) was only dependent on feed rate variations. Increasing rotation speed induced a large increase in dissipated power ($\dot{W}_{tot}$) whereas the

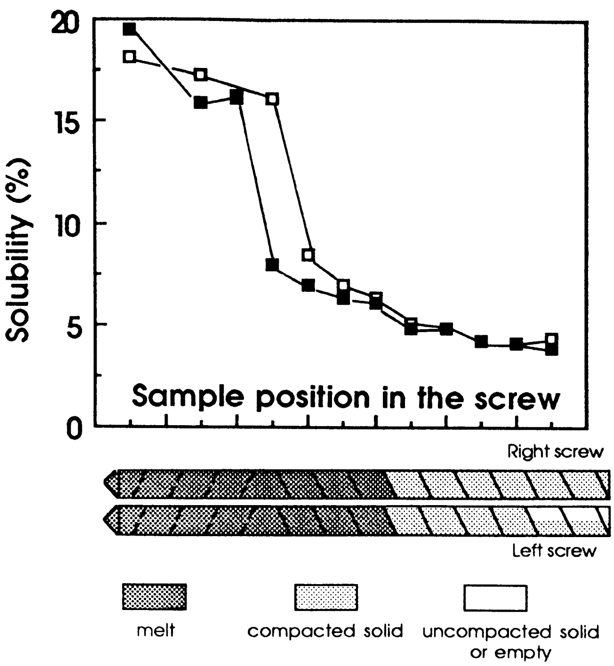

Fig. 4. Evolution of solubility along the screw. BC 45, 1 RSE, 10-mm-wide slots, feed rate = 30 kg/hr, rotation speed = 100 rpm: right screw (□), left screw (■).

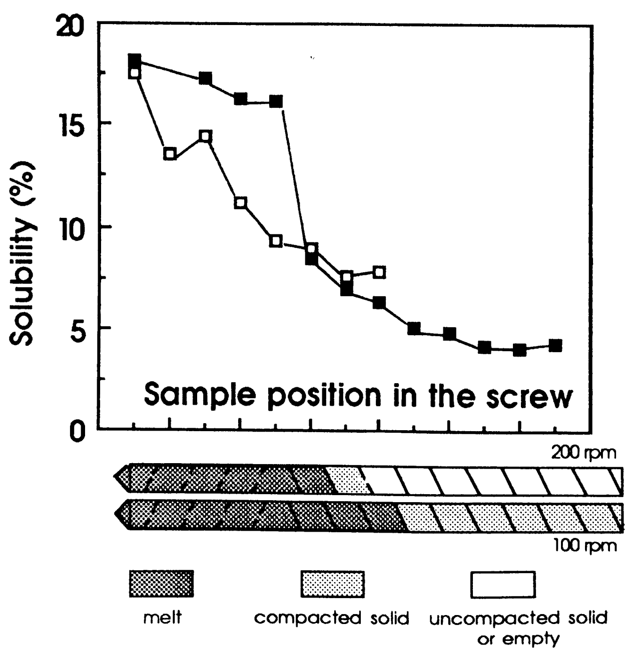

Fig. 5. Influence of rotation speed on solubility and degree of filling. BC 45, one reverse screw element, 10-mm-wide slots, feed rate = 30 kg/hr: 200 rpm (□), 100-rpm (■).

feed rate seemed to affect it very little. As a consequence, increasing the feed rate from 10 to 90 kg/hr on the BC 45 divided the SME by a factor of 10, whereas increasing the screw speed from 150 to 250 rpm multiplied it only by a factor of two (Fig. 9).

The length of the RSE had a great influence on SME, since both dissipated power and mean residence time were higher as the RSE lengthened (Fig. 10).

The width of the slots mainly affected the dissipated power. Beyond 6 mm, the SME remained quite constant. Under 4 mm, it increased tremendously and was multiplied by three when reducing the width from 8 to 3 mm (Fig. 11).

A comparison of the BC 45 and the BC 72 results is presented in Table II for different screw configurations and operating conditions. Mean residence times were found to be equivalent on both machines: 5–45 sec for one RSE and 10–35 sec for two RSEs, depending on feed rate. The total dissipated power ($\dot{W}_{tot}$) was generally higher on the BC 72 (400–2,500 W instead of 200–800 W on the BC 45). However, this power was dissipated in a larger amount of product and therefore the SME was hardly dependent on the size of the extruder.

Measurements of specific energy for twin-screw extruders led to values between 50 and 400 kWhr/t, depending on the product, the machine size and the measurement technique itself (Meuser and Van Lengerich 1984, Senouci and Smith 1986). A specific study on a Clextral BC 45 extruder (Della Valle et al 1989) showed that, for this machine in classical operating conditions, the energy really delivered to the product was in the range of 100 to 150 kWhr/t. The SME values from the preceding theoretical developments are lower than those found in these experimental papers and vary between 5 and 40 kWhr/t. This could be attributable to the simplifying assumptions on which the model relies and to the estimation of the rheological properties of wheat flour. Actually, the major reason for such a difference results from dealing with the RSE alone, whereas the experimental measurements necessarily included energy input in the whole machine. The minimum specific energy needed to increase the product temperature from ambient to melting temperature, and then to melt it, may be estimated by: $SME_{min} = Cp\Delta T + \Delta H$ (where Cp = specific heat, ΔT = temperature increase, and ΔH = enthalpy of fusion). For a wheat flour and average processing conditions, this value is found to be around 70 kWhr/t. This result means that a great part of the total SME is consumed in the melting before the RSE and that the order of magnitude of the computed SME is good, even if the values seem very low. Moreover, the evolutions of the theoretical SME allow one to explain the solubility results reported previously.

Several papers reported that increasing feed rate at constant rotation speed causes a decrease in the residence time in the whole extruder (Altomare and Ghossi 1986, Bounie and Cheftel 1986), which lowers the level of transformation. Figures 1 and 9 exhibit, respectively, evolutions of solubility of the extrudate and computed SME that are in good agreement. Both screw speed and flow rate may change the level of solubility, but in the usual operating range, the flow rate, which affected mainly the residence time, had more influence than the screw speed, which modified only the dissipated power.

The variation of SME with the length of RSE was also similar

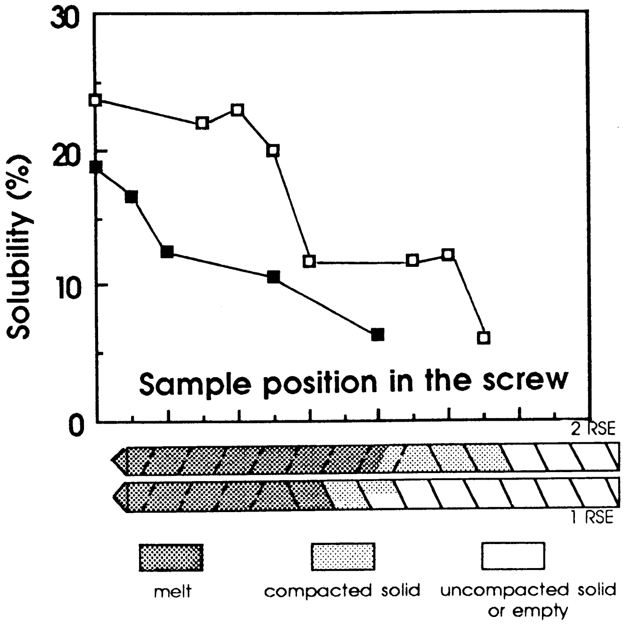

Fig. 6. Influence of reverse screw element (RSE) length on solubility and degree of filling. BC 45, 6-mm-wide slots, feed rate = 30 kg/hr, rotation speed = 200 rpm: 1 RSE (■), 2 RSE (□).

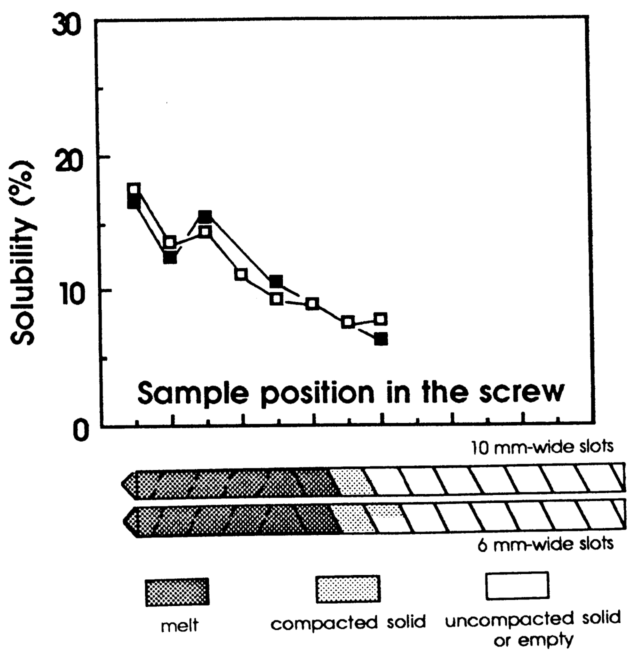

Fig. 7. Influence of slot widths on solubility and degree of filling. BC 45, one reverse screw element, feed rate = 30 kg/hr, rotation speed = 200 rpm: 6 mm (■), 10 mm (□).

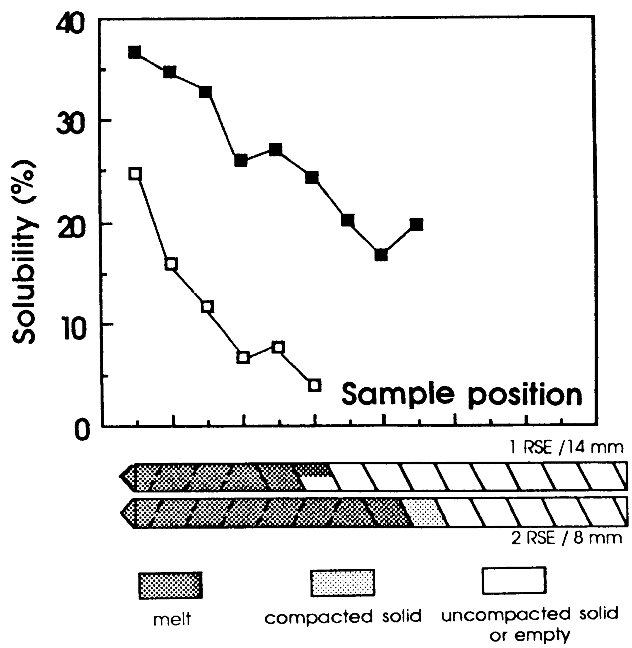

Fig. 8. Influence of reverse screw element (RSE) configuration on solubility and degree of filling. BC 72, feed rate = 80 kg/hr, rotation speed = 130 rpm. Moisture content = 17.6% (wb): 1 RSE, 14-mm-wide slots (□); 2 RSE, 8-mm-wide slots (■).

to the one of solubility (Figs. 2 and 10). At a given screw speed and flow rate, the power dissipated (and then the SME) increased with RSE volume. In the range of axial slot widths which were experimentally tested (6–10 mm), SME remained quite constant, and no influence was observed on solubility. A complementary experiment was attempted on the BC 45 with 3-mm-wide slots. Extrusion was impossible, with the product stopping and burning in the screws. In the same manner, Tayeb et al (1988) reported calculations in the RSE that exhibited an intensified growth of pressure drop through the RSE when the width of the slots was lower than 4 mm. These violent increases in computed SME and pressure drop might provide an explanation to the problems encountered experimentally with narrow slots.

In summary, it clearly appears that the transformation of the product can be estimated from computed specific energy locally dissipated in the RSE. Further developments of the theoretical model, including better description of the flow and computation of specific energy distribution, should enable us to improve these preliminary results. However, the actual model is already an interesting tool to provide information on the influence of processing conditions on product transformation.

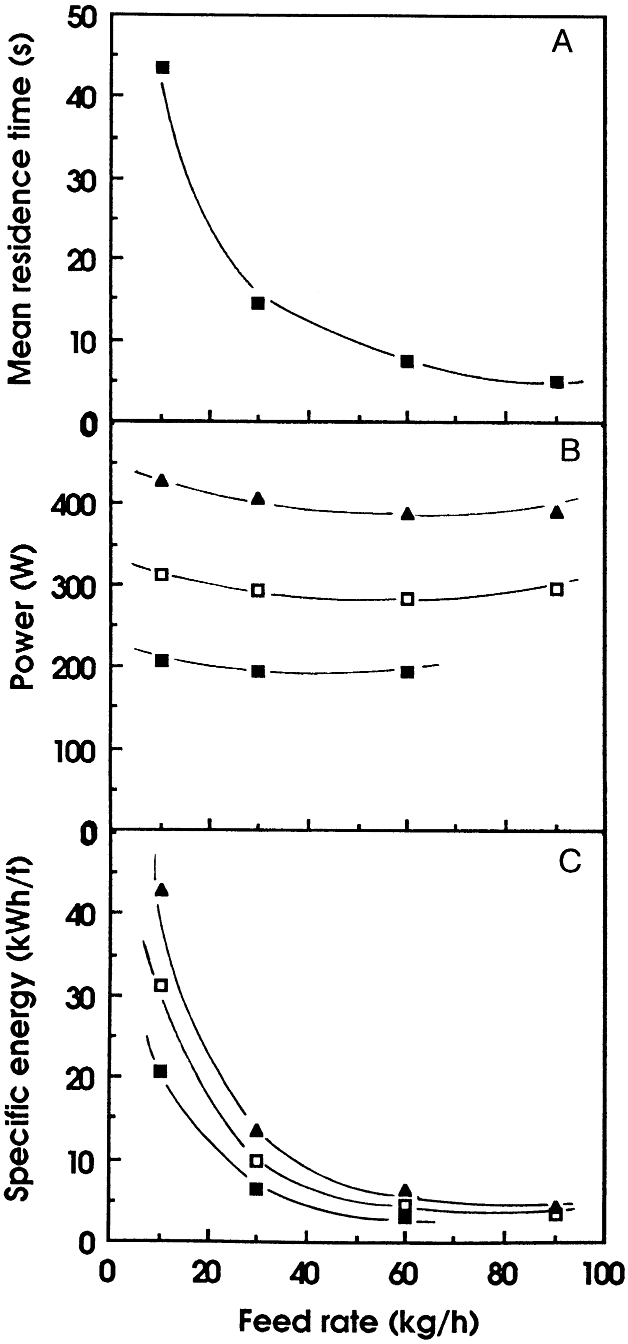

Fig. 9. Influence of feed rate and rotation speed on **A,** computed mean residence time; **B,** dissipated power; and **C,** specific mechanical energy. BC 45, one reverse screw element, 8-mm-wide slots: 150 rpm (■), 200 rpm (□), 250 rpm (▲).

CONCLUSION

The transformation of wheat flour in extrusion cooking was estimated from solubility measurements. Dead stop procedures allowed the transformation along the screw to be examined; it began in the compacted solid zone and developed progressively in the melt and pumping zones, with important variations at the entrance of RSEs.

The transformation was even more extended as the degree of filling was lowered (high rotation speed, low feed rate) and the geometry more restrictive to product flow. The length of the RSE was a significant parameter, whereas the width of the axial slots had less influence, at least in the classical ranges.

Computed SME was obtained from calculations of dissipated power and residence time in the RSE. The evolution of SME with processing conditions and RSE pattern (length, width of slots) was very similar to those of solubility and confirmed the dominant role of specific energy on product transformation.

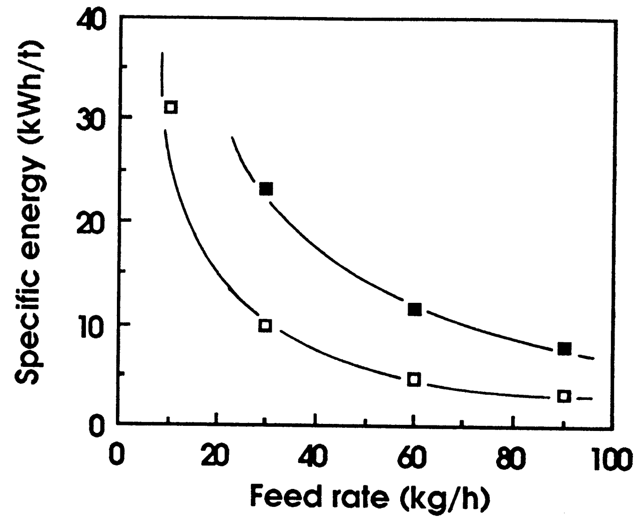

Fig. 10. Influence of number of reverse screw elements (RSE) on computed specific mechanical energy. BC 45, 8-mm-wide slots, rotation speed = 200 rpm: 1 RSE (□), 2 RSE (■).

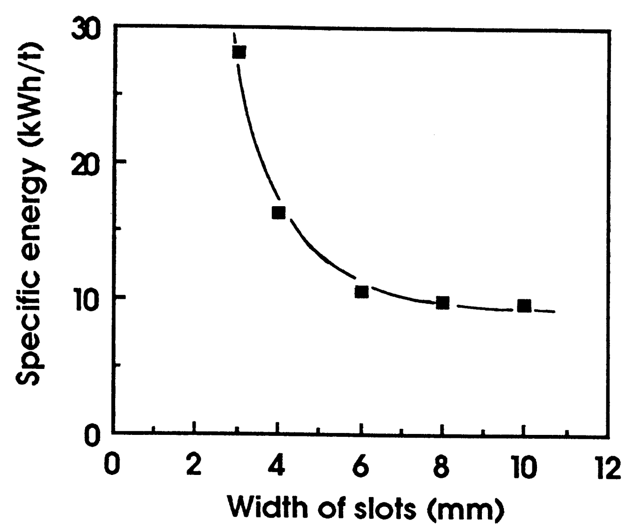

Fig. 11. Influence of slot width on computed specific mechanical energy. BC 45, one reverse screw element, feed rate = 30 kg/hr, rotation speed = 200 rpm.

TABLE II
Computed Values of Residence Time, Power, and Specific Energy in the Reverse Screw Element

Extruder/ (RSE/slot)[a]	N (rpm)	Q (kg/hr)	$\bar{t}$ (sec)	$\dot{W}_{tot}$ (W)	SME[b] (kWhr/t)
BC45					
1 RSE/8 mm	150	10	43.6	206	20.6
	150	30	14.5	193	6.4
	150	60	7.3	194	3.2
	200	10	43.6	312	31.2
	200	30	14.5	294	9.8
	200	60	7.3	284	4.7
	200	90	4.8	296	3.3
	250	10	43.6	430	43.0
	250	30	14.5	408	13.6
	250	60	7.3	390	6.5
	250	90	4.8	391	4.3
2 RSE/8 mm	200	30	29.1	700	23.3
	200	60	14.5	697	11.6
	200	90	9.7	721	8.0
1 RSE/3 mm	200	30	13.9	845	28.2
1 RSE/4 mm	200	30	14.0	490	16.3
1 RSE/6 mm	200	30	14.3	318	10.6
1 RSE/10 mm	200	30	14.8	290	9.7
BC72					
1 RSE/8 mm	80	120	17.5	579	4.8
	130	120	17.5	1,033	8.6
	130	160	13.1	1,082	6.8
1 RSE/14 mm	80	80	27.2	384	4.8
	130	160	13.6	751	4.7
2 RSE/8 mm	80	120	35.0	1,339	11.2
	130	120	35.0	2,347	19.6
	130	160	26.3	2,489	15.6

[a]Number of reverse screw elements (RSE)/width of slots.
[b]Specific mechanical energy.

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