

## Rheological and physical characterization of pregelatinized maize starches

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Received 3 November 2000; accepted 19 April 2001

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### Abstract

This work studies maize starches modified by a small-scale industrial double drum dryer. The impact of the processing thermal treatment is examined with respect to the morphology, texture and color of the dry product sheets. Moisture absorption/desorption tests are employed to evaluate the moisture exchange capability of the product sheets and also infer information about its bulk porosity. The variation of the intrinsic and apparent viscosity of the pregelatinized starches reconstituted with water to pastes is examined when the steam pressure, drum speed and level of the gelatinization pool between the drums are varied. Evidence is provided that the dispersed swollen starch granules control the rheological behavior of the starch pastes. © 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Drum drying; Pregelatinized starch; Morphology; Texture; Color; Moisture exchange; Intrinsic viscosity; Apparent viscosity

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### 1. Introduction

Pregelatinized starches, also referred to as instant starch slurries, are those that have been simply pre-cooked and drum dried to give products that readily disperse in cold water to form moderately stable suspensions (Hodge & Osman, 1976). Such products are used mainly as thickeners in foods and as adhesives in foundry core binders and in the textile industry (Colonna, Buleo, & Mercier, 1987). Drum-drying results in specific physicochemical modifications of starch granules performed in two consecutive stages: gelatinization and drying. In a double drum dryer, gelatinization takes place inside the “pool” of material formed between the upper halves of two horizontal drums. The actual drying starts only after the gelatinized material leaves the pool through the narrow gap between the drums and forms a thin film upon the surface of the drums. Drum-drying is capable of imparting a variety of textures and porous structures to the product – dictated strongly by the intensity of the treatment – which are expected to influ-

ence its functional properties (Bonazzi et al., 1996). Among them, the affinity of the dried sheets to moisture exchange makes the automatic control of drum-drying equipment very cumbersome due to the short response time required for an on-line moisture measurement (Vlachos & Karapantsios, 2000).

A number of papers examined the characteristics of single drum dryers as regards industrial applications. Most of them evaluated the performance of a dryer in terms of the throughput rate and/or moisture content of the end product e.g., Kozempel, Sullivan, Craig, and Heiland (1986); Fellows (1988). Moreover, it was well recognized that running a drum dryer is actually beset with many complexities due to the exceeding interaction among all operation variables (Daud & Armstrong, 1987; Trystram & Vasseur, 1992).

Studies dealing with double drum dryers are rather scarce and mainly of technological orientation. Kitson and MacGregor (1982) used a double drum dryer of novel design to dry fruit purees. These products because of their relatively high sugar content present thermo-plastic behavior when they are hot so their removal from the dryer required modifications of the exit section of the equipment. Rosenthal and Sgarbieri (1992) gave the response curves of a double drum dryer in terms of

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process yield, moisture content and some nutritional properties of dehydrated sweet corn pulp as a function of steam pressure and speed of rotation.

A survey of the literature shows that there is little information about the variation of the rheological and functional properties of drum dried starches with respect to different operating conditions. Fritze (1973) compared the response of four different types of drum dryers – including a double drum dryer – on drying maize starch slurries of different concentrations. The double drum dryer in that work was operated only at a fixed steam pressure and drums rotation speed so as to maintain a specific product moisture. Apart from the dryers' performance, some properties of the dry product such as water absorptivity, viscosity, cold water solubility, were examined as functions of the feed concentration. A more systematic analysis of the morphological and functional properties of pregelatinized starches was presented by Colonna, Doublier, Melcion, de Monredon, and Mercier (1984), Doublier, Colonna, and Mercier (1986). However, the primary intention of the above studies was to contrast the modifications imparted by drum drying against extrusion cooking so the dryer was operated only at fixed conditions. Moreover, a single drum dryer was employed and possible differences with the products of a double drum dryer are a matter of concern.

The purpose of the present work is to characterize the thermally modified starches produced by a small industrial-scale double drum dryer over a useful range of operating conditions. In particular, the effect of the process input variables (steam pressure, gelatinization pool level, drums rotation speed) on the moisture absorption/desorption capability of the dry sheets as well as on the intrinsic and apparent viscosity of the product being re-dispersed in cold water is examined. The aforementioned properties are of a paramount importance for practical applications.

## 2. Materials and methods

### 2.1. Materials and processing

Commercial maize starch was purchased from Group Amylum S.A., Greece, with a moisture content of 13.5%. The total amylose content is  $26.0 \pm 0.3\%$ , determined by the method of Morrison and Laignelet (1983). The volumetric granule size distribution determined by a Malvern MasterSizer (Malvern Instruments) laser diffraction particle size analyzer is essentially unimodal over the range 6–30  $\mu\text{m}$  with only a very small fraction of particles below 3  $\mu\text{m}$ . The granules mean diameter is 14.95  $\mu\text{m}$  with a S.D. of 5.8  $\mu\text{m}$ .

Native maize starch is modified by a double drum dryer (GOUDA). The drums have 0.5 m diameter and

0.5 m length and are synchronously driven at a rotational speed which is varied over the range 2–7 rpm. The drums are internally heated by steam at 6, 7 or 8 bars. The level of the free surface of the liquid pool between the two cylinders is meticulously regulated to 14, 18, or 22 cm above the gap – the nearest point between the drums. The gap setting at ambient conditions is 0.9 mm. For the major part of this study, starch/water suspensions with solids concentration of 10% w/w are employed as the dryer feed. A few runs with 7% and 13% are also conducted.

### 2.2. Macroscopical and microscopical evaluation

Mass flow rate is measured by collecting and timing large amounts of dry starch sheets as they come off the drums. Moisture content of the starch sheets is determined by drying a sufficient quantity to constant weight. The thickness of the sheets is measured by a digital micrometer with a resolution of 1  $\mu\text{m}$ . To grade the surface roughness and morphology of the dry sheets, optical microscopy and stereomicroscopy are employed. The brightness of the end product is measured by a colorimeter (Micro Color LMC, Dr. Lange) in accordance with the standardized sensory perception method (DIN 6174, 1976). Only the  $L^*$  values are utilized here which specify the brightness on a percentage basis along the light-dark axis (white = 100% – black = 0%). Each determination is repeated ten times for each of the three different samples taken from the same dry sheet. The average variance (= S.D./mean) of measurements is better than 0.05.

### 2.3. Moisture absorption/desorption measurement

Two types of moisture/dry starch interactions are investigated. The first one involves hydration of the dry sheets by application of Congo red dye to stain swollen particles and further inspect the hydration pattern and rate. The second type deals with moisture exchange with ambient air in order to demonstrate the importance of obtaining rapid moisture measurements of the starch sheets as they come off the drums. For this, the samples are placed on a sensitive balance standing inside an environmental chamber which is regulated at 22°C and 55% relative humidity. Indirect gross information regarding bulk porosity can be inferred from both types of interaction. Three separate tests are conducted for every sample.

### 2.4. Intrinsic viscosity measurement

The determination of the intrinsic viscosity is based on the method developed by Greenwood (1964). According to this method, a predetermined quantity of dry sheet fragments is initially dissolved in 1 M KOH (21°C)

to form a very dilute solution ( $\approx 5$  mg/ml). The solution is agitated for 20 min, filtered under reduced pressure and, finally, placed in a thermal regulated ( $21^\circ\text{C}$ ) capillary viscometer (Ubbelohde type). There, additional dilutions with KOH 1 M are progressively performed to give five different concentrations in the range 1–5 mg/ml. The intrinsic viscosity of the starch solution at infinite dilution is obtained by extrapolating the specific viscosity values measured for the successive dilutions. Each measurement is replicated three times. The average variance is less than 0.02.

### 2.5. Apparent viscosity measurement

Most measurements are conducted with mixtures of 4% w/w solids content and only a few tests with 3.5%, 4.5% and 6.4% mixtures. Two pasting procedures are employed. In the first one, dry sheet fragments are gradually added into a water flask placed in a shaking bath at  $40^\circ\text{C}$ . The final mixture is left inside the shaking bath for 15 min. The second procedure starts with a grinding step of the dry sheets performed at a planetary mill for 10 min (160 rpm). The finely ground product is then dispersed very slowly in water at  $40^\circ\text{C}$  while manually stirring to avoid the formation of lumps. In both pasting procedures, the mixture is agitated at the end by a magnetic spin bar for five more minutes in order to ensure homogeneity. It is hoped that the first pasting procedure can give more representative results avoiding probable modifications imparted by the intense mechanical action during the grinding step. The final mixture has always a characteristic pasty texture with no discernible clumps or air bubbles. This was indirectly verified by doing preliminary tests with prolonged heating/agitation periods up to 1 h that gave deviations in the viscosity less than 1%. Drying aliquots to constant weight always checks the final starch concentration.

Steady shear data of the rehydrated starch pastes consisting of shear stress, shear rate, time, temperature and apparent viscosity are obtained using the cone ( $2.5$  cm,  $3^\circ$ ) and plate arrangement of a Brookfield viscometer (RVTD VII/C-P, Brookfield Engineering Laboratories). The samples are submitted to consecutive shear rate steps from 1 to  $200\text{ s}^{-1}$  and subsequently back to the initial shear rate. All measurements are made at  $40^\circ\text{C}$ . At least three records are acquired for each sample to check for repeatability and further increase the statistical confidence of the estimated values. The deviation among measurements of repeated samples is generally less than 5% whereas the average variance ( $=\text{S.D./mean}$ ) is beyond 0.02. The selection of  $40^\circ\text{C}$  for pasting and further measurement of the apparent viscosity surmounts the syneresis phenomena encountered at lower temperatures (Stainsby, Ring, & Chilvers, 1984) and also diminishes the evaporation losses occurring at higher temperatures. Evaporation was repeatedly

witnessed as condensate droplets adhered to the inside walls of the viscosity test cup when measurements were initially tried at  $60^\circ\text{C}$ .

The final selection of all data is based on a systematic scrutiny of experimental errors and further rejection of extreme outliers. Results from the two drums are in close proximity so no differentiation is made in presenting them but instead single mean values are calculated. The [x-x-x] format in the legends of the plots stands for [steam pressure (bars) – pool level (cm) – rotation speed (rpm)].

## 3. Results and discussion

### 3.1. Residence time of material inside the gelatinization pool

The throughput rate of the dryer together with the pool volume can give the residence time of the slurry in the pool. The pool volume is estimated as 1950, 4300 and 8350 ml, for pool levels at 14, 18 and 22 cm, respectively. The residence time reflects the period the material spends for gelatinization. Spatial inhomogeneities in the bulk density and moisture of the material in the pool allow only for average estimations of residence times. For the employed experimental conditions, the residence times vary approximately between 3 and 15 min, Fig. 1. The shorter times correspond to higher rotation speeds, lower pool levels and lower steam pressures (not shown). The order among the three input variables towards the one with the least significant effect is: pool level, rotation speed and steam pressure. Furthermore, it is observed that for the range of our experimental parameters, moisture losses during gelatinization inside the pool are less than 3% of the total

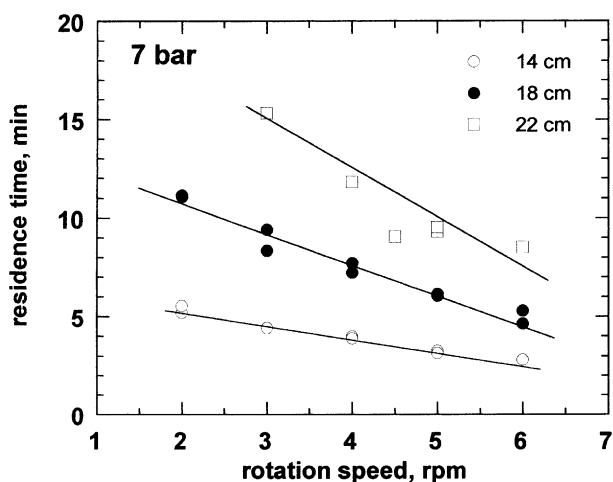


Fig. 1. Residence times of material inside the gelatinization pool with respect to rotation speed and level of the pool (volume of material).

weight for all operating conditions with inferior consequences to the film drying that follows.

### 3.2. Morphology and texture of dry product

In all dried sheets the granular shape of starch is completely absent. Instead, the sheets look like a composite medium in which air bubbles are randomly distributed inside the continuous solid phase at comparable volume fractions. It appears that the space vacated by the evaporating moisture during drying is not (fully) compensated by sheet shrinkage due perhaps to the sharp increase of viscosity upon drying. Besides, a perfect contact between the product layer and the drum surface is very unlikely to occur but instead tiny gaps rather exist filled with either air or vapor. These gaps not only create a considerable resistance to heat transport but also promote the entrapment of air bubbles to the solid phase (Wang, Qiu, & Wang, 1990).

Over the limited range of employed conditions, the sheets produced by the drum-dryer have a thickness approximately between 0.04 and 0.09 mm with the lower values persistently corresponding to the higher rotation speeds and higher moisture contents. Moderate fluctuations (up to  $\pm 7\%$ ) are frequently observed in the thickness of the product as a result of perturbations in the drying process. Such phenomena are often encountered in drum drying and are responsible for producing unevenness in the moisture distribution of the final dried product, e.g. Rodriguez, Vasseur, and Courtois (1996).

The appearance of the product is different at the two sides of the sheet. In general, the side in contact with the drum surface is smooth and flat whereas the other (free) side is irregular with more or less prominent ridges. These observations are in accord with the description of Colonna et al. (1984) for drum dried wheat starches. For products with moisture content between 2% and 6% (w.b.) the material is opaque, bright white and quite firm. In addition, the sheetfree-surface looks pretty homogeneous. For moisture contents between 7% and 12% the sheets surface becomes more irregular and small stains “butterflies” appear all over. For moistures above 15%, the material develops a semitransparent appearance with many evident wetter spots across the sheet. Fig. 2 displays brightness versus moisture content of the end product produced at a steam pressure of 7 bars. Despite the appreciable scatter, there is an apparent trend of high  $L^*$  values for low moisture contents. The scatter observed in Fig. 2 is mainly attributed to the non-uniform moisture across the dry sheets where wetter zones alternate with dryer ones (Rodriguez et al., 1996). So, while the  $L^*$  values correspond to spot measurements from individual pieces of the dry sheet, the moisture values are averages determined from much larger quantities of the dry product. Nevertheless, optical colorimetry appears to have some potential for actual

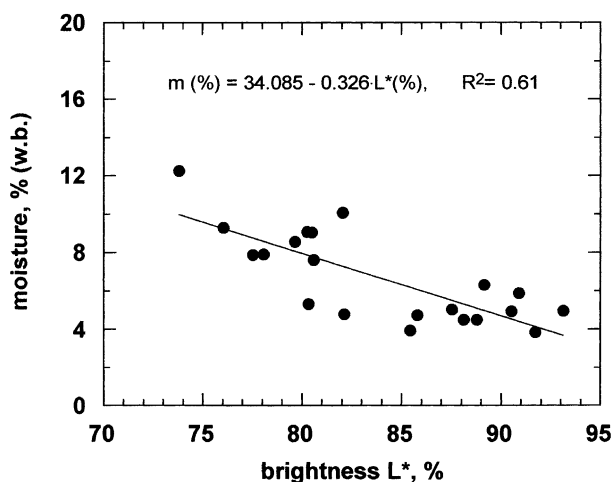


Fig. 2. Moisture content versus brightness for sheets produced with a steam pressure of 7 bars and for all employed pool levels and rotation speeds.

on-line measurements of the dry sheet moisture content. Work in that direction is underway.

### 3.3. Moisture absorption/desorption characteristics of dry product

The obtained drum-dried sheets present excellent wettability and are easily dispersible in cold water. Our hydration tests show that the dryer the samples the more wettable. A comparatively rapid expansion of the dye front is observed for the first few centimeters, beyond which the spreading speed decays to much lower values. Naturally, we noticed that the larger the available area for dye spreading (in the range 4–100 cm<sup>2</sup>) the more time the dye required to spread. Colonna et al. (1984) and Doublier et al. (1986) mentioned that during drum drying, where no shear is applied to the swollen granules, just a partial leaching of amylose occurs while starch components are only slightly depolymerized and probably remain entangled inside a continuous matrix. Thus, the drum dried products present a high water accessibility (due to their loose structure) and only a limited cold water solubility (due to the high molecular weight starch components). The present observations are in line with the evidence communicated by those researchers at least as regards the cold water accessibility of drum dried starches.

Fig. 3(a) depicts moisture absorption/desorption experiments from ambient air with drum dried sheets obtained at a steam pressure of 7 bars, pool level 18 cm and for rotational speeds between 2 and 7 rpm. Replicate curves for the same speed represent samples of different initial weights;  $\sim 50$ ,  $\sim 200$  and  $\sim 600$  mg. Samples produced at high rotational speeds (6 and 7 rpm) have higher initial water content and appear to rapidly desorb moisture towards an equilibrium stage.

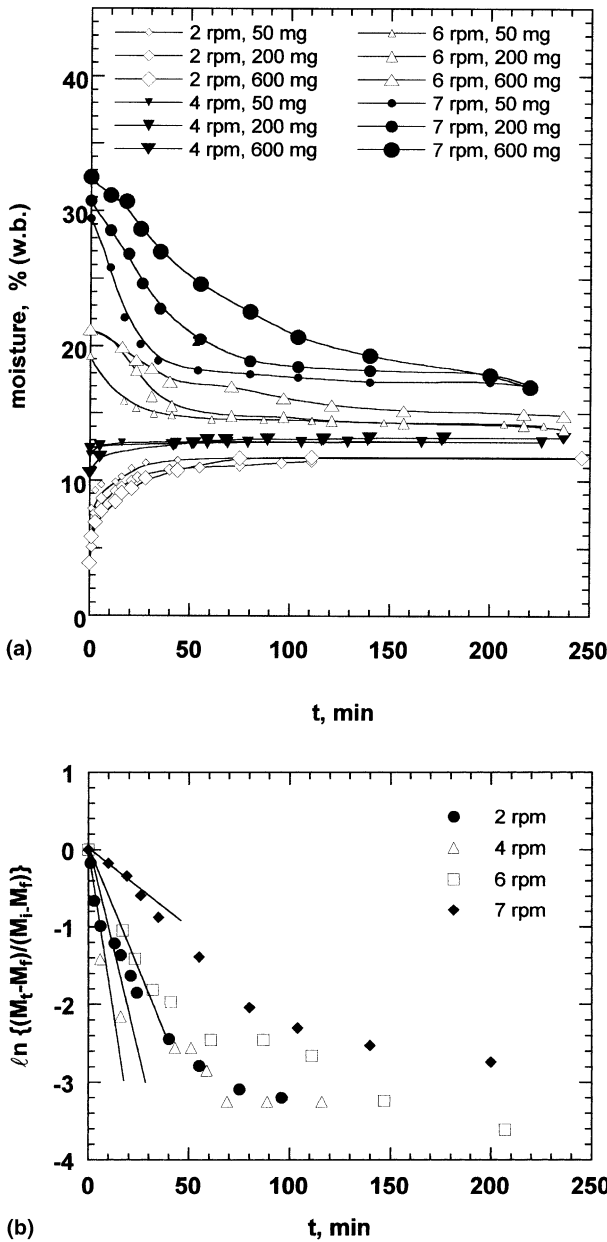


Fig. 3. (a) Moisture absorption/desorption versus time of as-sampled starch sheets (7 bars – 18 cm). Replicates correspond to samples of different initial weights. (b) Semi-log plot of unaccomplished moisture exchange fraction as a function of time. The straight lines represent pseudo first-order kinetics calculated for the first 20 min.

On the contrary, the initial water content of samples treated at low speeds (2 and 4 rpm) rapidly increases by absorption towards equilibrium. The equilibrium stage appears to be around the moisture value of the purchased commercial maize starch (13.5%). In all cases, few minutes are just enough for sample moisture to change drastically. Interestingly, appreciable differences are observed even between replicate curves. This is so because, apart from the 50 mg samples, the sheets of the other samples are folded to fit inside the measuring dish and so part of their surface is hindered from a fully free

contact with the surrounding air. This may be responsible for a less rapid moisture exchange.

Under isothermal conditions, the extent of absorption/desorption can be expressed in terms of the dimensionless ratio

$$\Phi = \frac{M_i - M_t}{M_i - M_f}, \tag{1}$$

where  $M_t$  is the instantaneous,  $M_i$  is the initial and  $M_f$  the final moisture contents of the product sheet. One might argue that the equilibrium moisture content,  $M_e = 13.5$ , should be used instead of  $M_f$ . However, if the objective is to study the kinetics at the early stages of moisture exchange then the deviation associated with the use of  $M_f$  is diminished. Based on the unaccomplished mass exchange fraction, Eq. (2) describes the absorption/desorption rate assuming pseudo-first-order kinetics:

$$\frac{d\Phi}{dt} = k_1(1 - \Phi), \tag{2}$$

where  $k_1$  is a kinetic rate constant which can be evaluated from semi-log plots based on Eq. (3)

$$\ln \frac{M_t - M_f}{M_i - M_f} = -k_1 t. \tag{3}$$

Fig. 3(b) displays the kinetic curves of the experiments presented in Fig. 3(a). Only the curves of the 50 mg samples are plotted as they represent the most rapid phenomena. Clearly, the assumption of first-order kinetics is not valid over the entire period. However, this approach would be adequate in describing absorption/desorption in short times, which is the concern for the automatic control of a drum dryer. Use of a restricted time range for the analysis is not uncommon in kinetic studies of starch systems, e.g., Okechukwu and Rao (1996). Kinetic constants calculated from data for the first 20 min are displayed in Table 1, ( $k_1$ ). The sample at 4 rpm presents the fastest whereas the sample at 7 rpm the slowest mass transport rate. This may be so because a dry porous medium hydrates easily while a wet porous medium dehydrates with difficulty (Adamson, 1982).

To check further on the material characteristics upon water uptake, some absorption tests are conducted with drum-dried samples (7 bars – 18 cm) completely dried first (to zero moisture) and then placed inside the environmental chamber. The balance readings taken from time to time are shown in Fig. 4(a). In all runs, the absorption curves appear to have the same overall pattern although the scatter within the main path of the curves is appreciable (variance 0.1), with no obvious dependence on rotational speed. One can further see that the moisture content increases markedly with time (towards an equilibrium stage). The equilibrium stage is initially approached at a considerably faster rate than in the experiments of Fig. 3. The resemblance among the absorption curves of Fig. 4(a) is remarkable especially if

Table 1  
Pseudo-first-order kinetic constants for moisture absorption/desorption of starch sheets

rpm	Rate constant $k_1$ ( $\text{min}^{-1}$ )	$R^2$	Rate constant $k_2$ ( $\text{min}^{-1}$ )	$R^2$
2	0.078	0.865	0.077	0.993
3	–	–	0.072	0.991
4	0.128	0.898	0.082	0.987
5	–	–	0.066	0.935
6	0.062	0.999	0.063	0.969
7	0.018	0.999	–	–

Moisture exchange of the as-sampled sheets for the first 20 min is described by  $k_1$  whereas  $k_2$  refers to moisture uptake of initially completely dried sheets for the first 50 min.

one considers the variations observed in the morphology and texture of the samples treated at different rotational speeds.

The semilog plots based on Eq. (3) are shown in Fig. 4(b). Up to about 50 min, all samples bear a common rehydration pattern which is adequately described by pseudo first order kinetics. Table 1 summarizes the

respective kinetic constants ( $k_2$ ). In view of the above, one might be tempted to argue that, within the range considered, the porosity of the dry product, which is the property most expected to influence moisture uptake, either does not vary so much as to alter the hydration behavior or varies but its effect is not so evident.

#### 3.4. Intrinsic viscosity of product solutions

Intrinsic viscosity measurements are customary used to grade the degree of granule breakdown and, in essence, the severity of the thermal treatment (Mercier, 1987). Fig. 5 shows the effect of the input variables (steam pressure, gelatinization pool level, rotation speed) to the intrinsic viscosity of the end product being reconstituted with water into a dilute solution. Fig. 5(a) clearly shows that when the pressure increases the intrinsic viscosity decreases. This is somewhat expected since then the drums attain higher temperatures which can intensify thermal processing (Vallous, Gavrielidou, Karapantsios, & Kostoglou, 2000). In drum drying, the chemical structure of starch is not altered so the lowering of the present intrinsic viscosity rather manifests that starch components degrade into macromolecules of lower molecular weight. Whether these modifications occur during the gelatinization stage in the pool or during the subsequent intense drying or both is a matter of concern.

Fig. 5(b) shows how the intrinsic viscosity varies with respect to pool level for a steam pressure of 7 bars. For low rotation speeds (2 and 3 rpm), the differences among measurements are insignificant ( $P > 0.95$ ). For higher speeds (4 and 5 rpm), though, a persistent decreasing trend is displayed. During the operation of the present drum dryer it has been observed that at such drum speeds, an increase in pool level is accompanied by a decrease in drums temperature but an increase in product's moisture content, mass flow rate and film thickness (Vallous et al., 2000). In view of the above, one would expect an ascend in viscosity, rather than a descend, with pool level since then the severity of drying seems to reduce. However, the possibility cannot be excluded that the residence time of the material inside

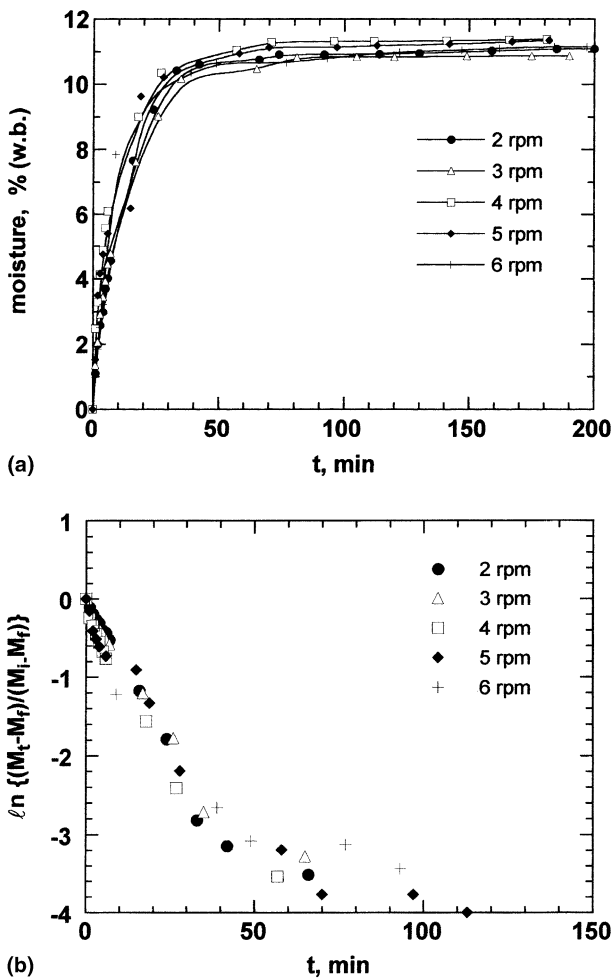


Fig. 4. (a) Moisture absorption versus time of initially completely dried starch sheets (7 bars – 18 cm). (b) Semi-log plot of unaccomplished moisture uptake fraction as a function of time.

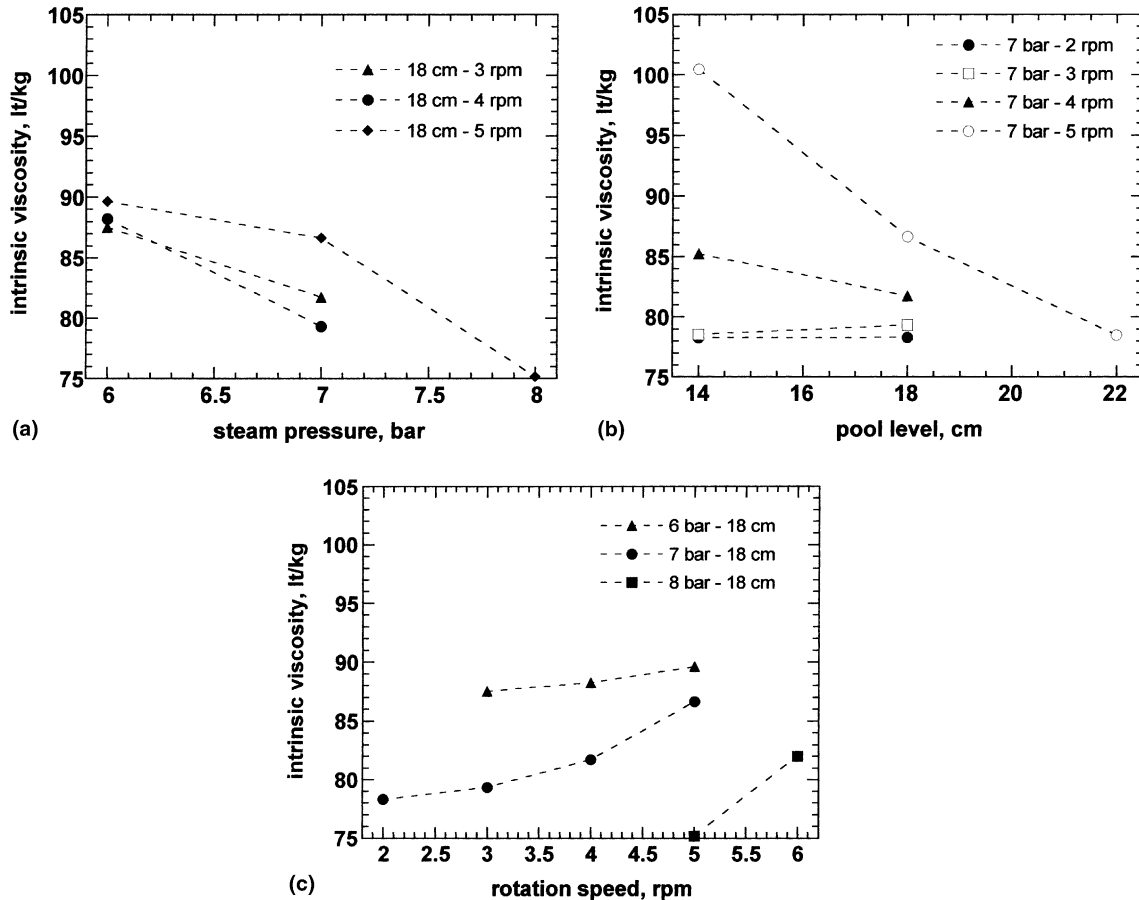


Fig. 5. Effect of the dryers (a) steam pressure, (b) pool level and (c) rotation speed, to the intrinsic viscosity of dilute starch solutions measured at 21°C.

the pool may play a critical role in this respect. If it is so, then it may be possible that at low pool levels there is simply not enough time (see Fig. 1) for the material to receive a hydrothermal alteration sufficient to lower its intrinsic viscosity. Fig. 5(c) shows that the intrinsic viscosity increases with rotation speed. It has been noticed that when the rotation speed goes up the drums temperature goes down but the product's mass flow rate and moisture go up (Vallous et al., 2000). All the above combined support the observations depicted in Fig. 5(c) that at higher rotation speeds the material receives a milder treatment and therefore its viscosity is higher.

Colonna et al. (1984) reported intrinsic viscosity values for pregelatinized wheat starches produced by a single drum dryer rotated at 10 rpm and heated by steam at a pressure of 10 bars. They reported an intrinsic viscosity value of 188 l/kg for the directly dried and 182 l/kg for the initially precooked and then dried starch. Much larger deviations were observed between drum drying and extrusion cooking since in the latter the material undergoes also a severe mechanical treatment (Colonna et al., 1984). Apparently, a direct comparison of these results with the present work is not possible.

### 3.5. Apparent viscosity of product solutions

Fig. 6 shows typical curves of apparent viscosity versus shear rate taken for a pregelatinized starch paste (unground sample) with a 4% w/w solids content at 40°C. These data are obtained by increasing and then decreasing the shear rate for several consecutive cycles. All flow curves are typical of a non-Newtonian shear thinning (pseudo-plastic) fluid with a slight thixotropy. It is apparent that the time-dependent effects diminish after the first two cycles. Therefore, data acquired during the ascending segment of the third shear cycle are used for flow characterization.

Over the entire range of shear rates a reasonable linear behavior is found in Fig. 6, with no evidence of a yield stress towards the low shear rates as previously observed for drum dried wheat pastes (Doublier et al., 1986). The data fit very well the power law equation

$$n_a = \frac{\sigma}{\dot{\gamma}} = K_V \dot{\gamma}^{\alpha-1}, \quad (4)$$

where  $n_a$  is the apparent viscosity,  $\sigma$  the shear stress (Pa),  $\dot{\gamma}$  the shear rate ( $s^{-1}$ ),  $K_V$  the consistency number ( $Pa s^\alpha$ )

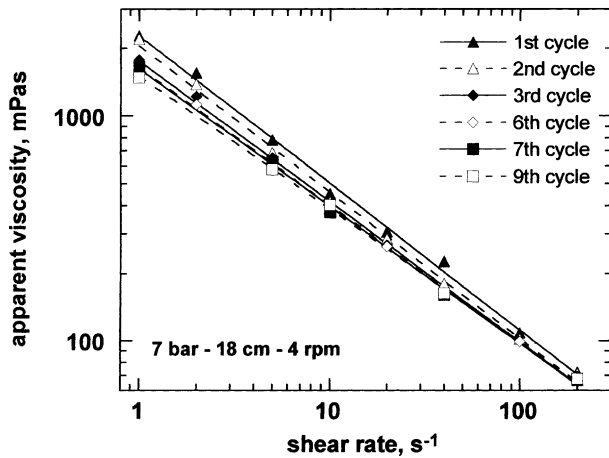


Fig. 6. Apparent viscosity versus shear rate curves measured at 40°C during several consecutive shear rate cycles. Starch pastes are made from unground dry sheets fragments (7 bars – 18 cm – 4 rpm) being re-dispersed in cold water to a 4% solids concentration.

and  $\alpha$  the flow behavior index (dimensionless). For all the flow curves of this study the flow behavior index varies from 0.34 to 0.44 with no significant ( $P < 0.05$ ) dependence on any of the input variables. The high values of  $R^2$  ( $>0.997$ ) confirm the suitability of the power law model in describing the flow behavior of the pregelatinized starch pastes over the indicated shear rate region. Furthermore, the same range of  $\alpha$  is found for pastes produced from feed suspensions of 7% and 13% (w/w) solids content (not shown). Although such concentrations give pool slurries with slightly different rheological behaviors, which apparently can affect the circulation and heat transport in the pool, the ultimate dry products possess the same non-Newtonian character when dissolved in cold water. The range of flow behavior indexes is lower than the range communicated by Doublier et al. (1986), for wheat starches pregelatinized in a single drum dryer; 0.6–0.7, measured at 60°C for concentrations between 5% and 9.5%. This discrepancy may be attributed, at least in part, to the different botanical origins and pasting procedures.

Contrary to the flow behavior index, the consistency number shows a marked dependence on all input variables. For clarity in the presentation, Eq. (4) can be written as

$$n_a = K_V^{100} (\dot{\gamma}/100)^{\alpha-1}, \quad (5)$$

where  $K_V^{100}$  is the consistency number corresponding to  $n_a$  at 100 s<sup>-1</sup>. This specific shear rate is chosen as a reference as it seems to represent a reasonable agitation rate for applications (50 rpm) and also permits comparisons with the work of Doublier et al. (1986). Besides, curve fitting with other shear rates as reference gives the same range of  $\alpha$  values so the selection does not really make a difference. Fig. 7 depicts the variation of  $K_V^{100}$  for unground samples with respect to the three input vari-

ables of the drum dryer. The consistency number displays an increasing trend with steam pressure, Fig. 7(a). The dependence of  $K_V^{100}$  with pool level is shown in Fig. 7(b). Clearly,  $K_V^{100}$  goes up when pool level goes up. The opposite trend is observed as regards the rotation speed of the drums, Fig. 7(c) (the data for 6 bars are statistically indifferent at  $p > 0.95$ ). Literature is scanty in this respect. Extrapolating the  $K_V^{100}$  – values measured at 60°C by Doublier et al. (1986, their Fig. 5) to a 4% wheat starch concentration gives a value around 30 mPas. Fritze (1973) reported an apparent viscosity of 80 mPas for a maize starch paste produced by a double drum dryer. Unfortunately, there is no information regarding the shear rate and temperature of measurement and the precise solids content of the paste (~5–10% w/w).

Holdsworth (1993) reported that both  $\alpha$  and  $K_V$  show a dependence on the concentration of the paste. Tests with materials produced at the same operating conditions of the drum dryer (7 bars – 18 cm – 4 rpm) and concentrations 3.5%, 4% and 4.5% are shown in Fig. 8. Although the apparent viscosity, and therefore  $K_V$ , increases with concentration, the flow behavior index is the same as with 4%. This is probably due to the employed narrow range of low concentrations, which do not allow prompt identification of any changes. Fig. 9 presents the effect of the pasting procedures – ground and unground samples – to the apparent viscosity of a paste with 6.4% solids content. The limited range of shear rates is dictated by the detection limits of the viscometer. It is apparent that pastes from ground samples give higher consistency values than pastes prepared directly from the dry sheets. This is in accord with the observations of Colonna et al. (1987).

Cross-inspection of Figs. 5 and 7 reveals that intrinsic and apparent viscosities are negatively correlated for the employed range of input variables. Recalling arguments advanced in Sections 3.3 and 3.4, one can view the intrinsic viscosity as a measure of starch solubilization and further molecular entanglement in the continuous phase. On the other hand, the apparent viscosity reflects the overall rheological behavior of the pastes which is influenced not only by the solubilized starch components but also by the swollen granules being dispersed in the continuous phase. Thus, the behavior seen in Figs. 5 and 7 manifests a competition between the swollen particles in the disperse phase and the solubilized starch components in the continuous phase. The smaller the size of the solubilized macromolecules and their possible interactions (smaller  $[\eta]$ ), the greater the volume fraction occupied by the swollen granules (Christianson, Baker, Loffredo, & Bagley, 1982; Okechukwu & Rao, 1995). Apparently, the opposing trends in Figs. 5 and 7 demonstrate that the rheological behavior of the pregelatinized starches is chiefly controlled by the swollen particles. This is also what Doublier et al. (1986) concluded about their pregelatinized wheat pastes.



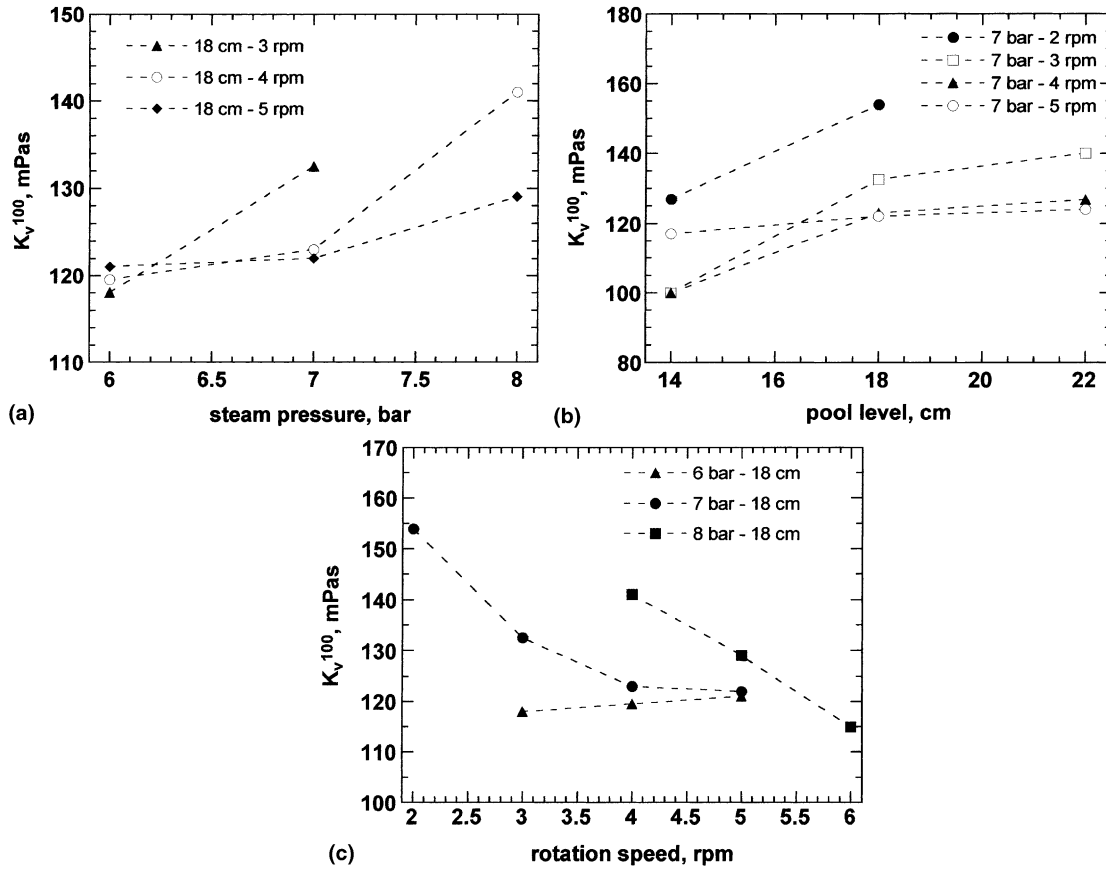


Fig. 7. Effect of the dryers (a) steam pressure, (b) pool level and (c) rotation speed, to the consistency number at  $100\text{ s}^{-1}$ , ( $K_v^{100}$ ), of starch pastes measured at  $40^\circ\text{C}$ . Pastes are made from unground dry sheets fragments being re-dispersed in cold water to a 4% solids concentration.

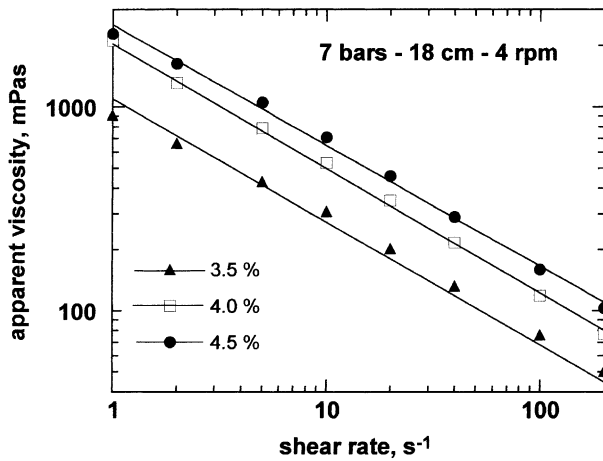


Fig. 8. Variation of the apparent viscosity of starch pastes with solids concentration. Pastes are made from unground dry sheets fragments (7 bars – 18 cm – 4 rpm).

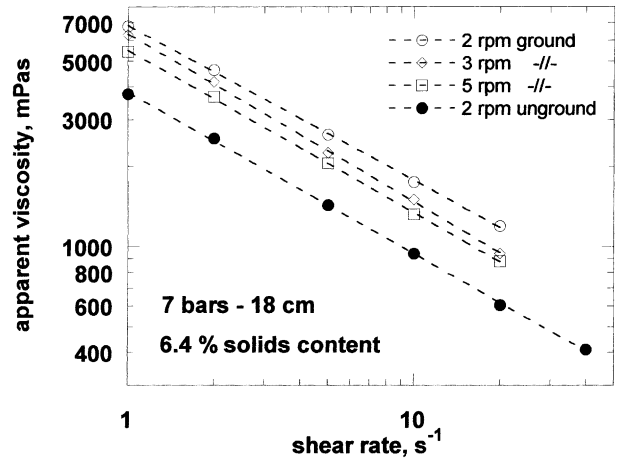


Fig. 9. Variation of the apparent viscosity of starch pastes with 6.4% solids concentration with respect to pasting procedure; ground versus unground dry sheets.

**4. Conclusions**

Drum drying imparts a number of morphological and textural characteristics to modified starches, reflecting strongly the intensity of the treatment. As shown by

moisture absorption/desorption tests, time may have a critical importance for moisture content determination in drum drying equipment. The moisture exchange of the just produced dry sheets with the environment varies with their initial water content. However, despite the varia-

tions in texture and morphology, the moisture uptake rate of the sheets being completely dried first is comparable among the employed operating conditions. This may indicate either minor differences in bulk porosity or just a small role being played by it. Furthermore, the operating conditions of a double drum dryer influence the rheological behavior of the pregelatinized starches reconstituted with water to weak pastes. In this respect, this is the first time that the possible effect of the residence time of the material inside the gelatinization pool is taken into account. Moreover, the present results support the notion that the swollen starch granules have an overwhelming contribution to the rheology of the pastes as compared to the solubilized starch macromolecules.

### Acknowledgements

Helpful discussions with professors S. Raphaelides and N. Georgiades are acknowledged.

### References

- Adamson, A. W. (1982). *Physical chemistry of surfaces* (4th ed.). New York: Wiley, pp. 332–364 and 433–458.
- Bonazzi, C., Dumoulin, E., Raoult-Wack, A., Berk, Z., Bimbenet, J. J., Courtois, F., Trystram, G., & Vasseur, J. (1996). Food drying and dewatering. *Drying Technology*, 14(9), 2135–2170.
- Christianson, D. D., Baker, F. L., Loffredo, A. R., & Bagley, E. B. (1982). Correlation of microscopic structure of corn starch granules with rheological properties of cooked pastes. *Food Microstructure*, 1, 13–24.
- Colonna, P., Buleo, A. & Mercier, C. (1987). Physically modified starches. In T. Galliard (Ed.), *Starch: Properties and Potential*. Critical Reports on Applied Chemistry (vol. 13, pp. 79–114). New York: Wiley.
- Colonna, P., Doublier, J. L., Melcion, J. P., de Monredon, F., & Mercier, C. (1984). Extrusion cooking and drum drying of wheat starch, I. Physical and macromolecular modifications. *Cereal Chemistry*, 61(6), 538–543.
- Daud, W. R. b. W. & Armstrong, W. D. (1987). Pilot plant study of the drum dryer. In A. S. Mujumdar (Ed.), *Drying '87* (pp. 101–108). New York: Hemisphere.
- DIN 6174 (1976). *Colorimetric evaluation of color differences*, CIE-LAB.
- Doublier, J. L., Colonna, P., & Mercier, C. (1986). Extrusion cooking and drum drying of wheat starch. II Rheological characterization of starch pastes. *Cereal Chemistry*, 63(3), 240–246.
- Fellows, P. (1988). Mechanism of Drying. In P. Fellows (Ed.), *Food processing technology* (pp. 284–306). Chichester: Ellis Horwood.
- Fritze, H. (1973). Dry gelatinized produced on different types of drum dryers. *Industrial Engineering Chemical Process Design and Development*, 12(2), 142–148.
- Greenwood, C. T. (1964). Viscosity-molecular weight relations. In R. L. Whistler Ed., *Methods in carbohydrate chemistry* (Vol. 4) (Starch) (pp. 179–188). New York: Academic press.
- Hodge, S. & Osman, M. (1976). Carbohydrates. In O. R. Fennema (Ed.), *Food chemistry, principles of food science part 1* (pp. 102–114). New York: Marcel Dekker.
- Holdsworth, S. D. (1993). Rheological models used for the prediction of the flow properties of food products: A literature review. *Transactions of the Institute of Chemical Engineers, Food and Bioproducts Processing* (Vol. 71) (part C), pp. 139–179.
- Kitson, J. A., & MacGregor, D. R. (1982). Technical note: Drying fruit purees on an improved pilot plant drum dryer. *Journal of Food Technology*, 17, 285–288.
- Kozempel, M. F., Sullivan, J. F., Craig, J. C., & Heiland, W. K. (1986). Drum drying potato flakes – A predictive model. *Lebensmittel-Wissenschaft und- Technologie*, 19, 193–197.
- Mercier, C. (1987). Comparative modifications of starch and starchy products by extrusion cooking and drum-drying. In C. Mercier, & C. Cantarelli (Eds.), *Pasta and extrusion cooked foods* (pp. 120–130). London: Elsevier Applied Science.
- Morrison, W. R., & Laignelet, B. (1983). An improved colorimetric procedure for determining apparent and total amylose in cereal and other starches. *Journal of Cereal Science*, 1, 9–20.
- Okechukwu, P. E., & Rao, M. A. (1995). Influence of granule size on viscosity of cornstarch suspension. *Journal of Texture Studies*, 26, 501–516.
- Okechukwu, P. E., & Rao, M. A. (1996). Kinetics of cornstarch granule swelling in excess water. In P. A. Williams, G. O. Phillips, & D. J. Wedlock, *Gums and stabilizers for the food industry-8* (Vol. 49). Oxford: Oxford university press.
- Rodriguez, G., Vasseur, J., & Courtois, F. (1996). Design and control of drum dryers for the food industry. Part I. Set-up of a moisture sensor and an inductive heater. *Journal of Food Engineering*, 28, 271–282.
- Rosenthal, A., & Sgarbieri, V. C. (1992). Nutritional evaluation of a fresh sweet corn drum drying process. In A. S. Mujumdar (Ed.), *Drying '92* (pp. 1419–1425). Amsterdam: Elsevier Applied Science.
- Stainsby, G., Ring, S. G., & Chilvers, G. R. (1984). A static method for determining the absolute shear modulus of a syneresing gel. *Journal of Texture Studies*, 15, 23–32.
- Trystram, G., & Vasseur, J. (1992). The modeling and simulation of a drum dryer. *International Chemical Engineering*, 32(4), 689–705.
- Vallous, N. A., Gavrieliidou, M., Karapantsios, T. D., & Kostoglou, M. (2000). Performance of a double drum dryer for producing pregelatinized maize starches. *Journal of Food Engineering*, in press.
- Vlachos, N. A., & Karapantsios, T. D. (2000). Water content measurement of thin sheet starch products using a conductance technique. *Journal of Food Engineering*, 46(2), 91–98.
- Wang, J. C. Y., Qiu, L. J., & Wang, S. F. (1990). Enhanced condensation inside a horizontal rotating drum-dryer. *Drying Technology*, 8(4), 829–843.