Effect of Feed Concentration on the Production of Pregelatinized Starch in a Double Drum Dryer

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An industrial-scale double drum dryer is operated for producing pregelatinized maize starches using feed starch slurries of different solids content. Steam pressure, the level of pool between the drums and speed of drums rotation are varied together with the feed solids content in a practical range of values. The response of the dryer is registered by measuring several output variables, i.e. external drum temperature, product moisture content, mass flow rate and specific load (equivalent to product's film thickness). Experiments are also conducted with a different steam pressure in each drum and by preheating the feed slurry. The measurements of this work demonstrate for the first time that the concentration-dependent rheological and transport properties of the drying material dominate the drying process over and above the thermal condition of the drums. This information combined with the notion of thick momentum boundary layers surrounding the drums at the region of the gap are employed to explain the material application as a thin film over the drums.

Keywords: drum drying; pregelatinized starch; film thickness; feed solids content

Introduction

The use of drum dryers is a common industrial practice for the production of a variety of foodstuffs such as yeast creams, fruit purees, baby foods, mashed potatoes, dry soup mixtures, pregelatinized starches, etc (Moore, 1995, Bonazzi *et al*., 1996). Pregelatinized starches are simply pre-cooked and dried starches that are readily dispersed in cold water to form stable pastes and are used mainly as thickeners in foods and as adhesives in the textile industry (Collona *et al*., 1987). The boiling type of drying involved in drum drying makes pregelatinized starches be indeed very porous and easy to rehydrate, ready to use (Vasseur *et al*., 1991*a*; Vlachos and Karapantsios, 2000).

A double drum dryer consists of two counterrotating horizontal cylinders of equal diameters, **Fig. 1**. The cylinders are hollow and are heated by steam condensing on their inside surface. One of the cylinders can be usually adjusted at right angles to its axis so that the gap between the two drums may be varied. The starch suspension is fed into the wedge-shaped space formed between the two drums (pool) where it heats up and gelatinizes. The gelatinized starch is calendered into a thin layer as it passes through the gap forced by the rotary action of the closely spaced drums. Right after the gap this layer splits into two films of gelatinized material, one for each drum. These films progressively dry as they rotate being adhered to the drums and are finally scraped off by 'doctor' blades extending the whole length of the drums. Thus, drum dryers are essentially conduction dryers, the drying effect being obtained by the transfer of heat from the condensing steam through the metallic body of the cylinders to the film of the material covering the external surface of the drums.

A survey of the recent literature shows that studies dealing with double drum dryers are rather scarce and are mainly of technological orientation. e.g. Kitson and MacGregor (1982) and Rosenthal and Sgarbieri (1992). On the contrary, several studies in the past have investigated systematically the performance of single drum dryers, e.g. Kozempel *et al*. (1986), Daud and Armstrong (1987), Daud (1988), Trystram and Vasseur,

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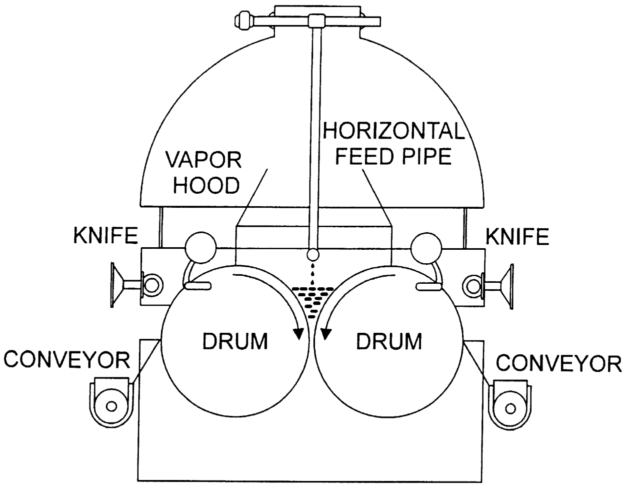

Fig. 1 Schematic representation of the employed double drum drier (GOUDA).

(1992), Rodriguez *et al.* (1996*a,b*) and Bonazzi *et al.* (1996). It is recognized that the presence of two drums in double drum dryers dictates quite distinct operational characteristics and direct comparisons with single drum dryers are not possible. For instance, in single drum dryers mass flow rate and film thickness depend very little on steam pressure since the gap is chiefly determined by the adjustment of auxiliary rollers. Conversely, in double drum dryers steam pressure is a major parameter influencing gap width (Gardner, 1971).

There are five input variables involved in the operation of a double drum dryer for a fixed feed material: (a) steam pressure, (b) speed of drum rotation, (c) gap between the drums, (d) pool level between the drums and (e) condition of the feed material, i.e. concentration, physical characteristics and temperature at which the material reaches the drum surface. It is noteworthy that most pertinent studies did not examine the effect of the condition of the feed material. Kozempel *et al.* (1990) studied the effect of potato composition on drum dryer capacity. To our knowledge, only Fritze (1973) varied *systematically* the solids content of the feed starch slurries in the range 15–40 g/100 g in comparing the performance of four different types of drum dryers. However, Fritze did not examine the effect of water evaporation during gelatinization in the pool to the solids content of the material before its actual film drying which in principle is a matter of concern.

Recently, Karapantsios and co-workers (Vlachos and Karapantsios, 2000; Anastasiades *et al.*, 2002; Gavrielidou *et al.*, 2002; Vallous *et al.*, 2002) communicated the results of a large experimental campaign (1997–2000) conducted on an industrial-scale double drum dryer. These studies aimed to investigate the complex phenomena governing the performance of a double drum dryer and also examine the influence of the dryer's operational characteristics on the properties of the end product. Yet the condition of the feed material was again not varied. The purpose of this work is to make this decisive step and investigate the effect of the different conditions of the feed material. Among them, special attention is paid to the role of the solids content of the feed slurry on the performance of the drum dryer. For this, the interaction among all input variables and their relation with certain output variables of the dryer (product moisture, mass flow rate, specific load) is examined.

Materials and Methods

Commercial native maize starch is purchased from GROUP AMYLUM S.A., Greece, with a moisture content of 13.5 g/100 g. The mean diameter of the granules is 14.95 μm with a standard deviation of 5.8 μm as determined in starch suspensions at 20 °C using a laser diffraction particle size analyzer (Malvern Mastersizer, Malvern Instruments). The total amylose content is 26 ± 0.3 g/100 g, determined by the method of Morrison and Laignelet (1983).

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 4, 5 or 6 rpm. The drums are internally heated by steam at 6, 7 or 8 bar. The level of the free surface of the liquid pool between the two cylinders is meticulously regulated (manually) at 14, 18, or 22 cm above the gap. The gap setting at ambient conditions is 0.9 mm. Starch/water suspensions with solids concentration of 7, 10 and 13 g/100 g (wet basis) are employed as the dryer feed. This range of concentrations is selected in order to get good-quality products given the range of the other input variables of the dryer. So suspensions with lower solids content get overdried and spontaneously detach from the drums before the doctor blades while suspensions with higher solids content are not adequately dried. The feed suspensions are prepared in a continuously agitated large tank (150 L) wherefrom a rotary positive displacement pump drives them to the dryer. A uniform distribution of the starch feed over the whole pool area between the drums is achieved by letting the suspension pass through a perforated horizontal tube, running the length of the drums, and free fall into the space between the drums. The feeding of the dryer is done only after the drums have reached their final stable temperature. After traveling 3/5 of a revolution, the dried product is removed in the form of thin sheets by the doctor blades. Samples of the dry product are collected with the dryer operating at steady state. Each experiment includes at least three measurements at every particular set of conditions. The average variance V (= s.d./mean) calculated from all measurements is less than 0.1. Results from the two drums are close to each other so no differentiation is made between them but instead single mean values are presented. Error bars in the plots of this work represent the standard deviation of measurements. In many cases, error bars are smaller than the employed markers.

Moisture content of the product sheets is determined by using the loss-in-weight technique. Mass flow rate is measured by collecting and timing large amounts of product sheets as they come off the drums. The rheological behavior of the different starch suspensions under dynamic heating is independently determined using an amylograph (Promylograph, Max Egger). The amylograph operates at 75 rpm and can provide three heating rates: 8, 4 and 2.5 °C/min. Spring-type thermocouples (Type K), designed for rotating surfaces, measure the temperature of the bare surface of the drums right after the doctor blades position. The temperature variation around the outside drum circumference is obtained by ultra-thin (0.1 mm) surface thermocouples (Type T) dressed with self-adhesive backing on one side to stick on the surface of the drums and insulation on the other side. These sensors once adhered to the drums travel with their speed until they are scrapped off by the doctor blades. In addition to the above, the spatial temperature distribution in the pool is also measured using a special construction furnished with 24 thermocouples (Kalogianni and Xynogalos, 2001). These detailed data are not presented here due to space limitations but since they qualitatively agree with measurements by Gavrielidou *et al.* (2002), reference to that earlier work is deemed adequate for the needs of the present study.

Repeatability checks are made for each set of conditions, giving satisfactory results. All thermocouples are calibrated to ± 0.1 °C at a certainty of 95%. The output of the thermocouples is sampled every 1 s using an ADAM 4018 16-bit A/D board (Advantec) interfaced to a PC.

Results and Discussion

Rheology of starch slurries

The rheological behavior under transient heating of starch/water slurries with 7, 10 and 13 g/100 g w/w (wet basis) solids content is shown in the amylograph curves of **Fig. 2**. The displayed curves are obtained with a heating rate of 8 °C/min, which is comparable to the mean heating-up rate of the slurry in the pool as evaluated by *average* residence times in the pool (Gavrielidou *et al.*, 2002). However, establishing a very precise and stable heating rate proved to have a minor effect since amylograms obtained with the other two lower heating rates (not shown here) bear no significant differences. It is evident from **Fig. 2** that despite the relatively small difference in solids, the viscosity of the slurries varies considerably. This was reported also by Xu and Raphaelides (1998) who worked with the same starch and manifests the strong influence of the gelatinized starch granules on the flow properties of the slurry.

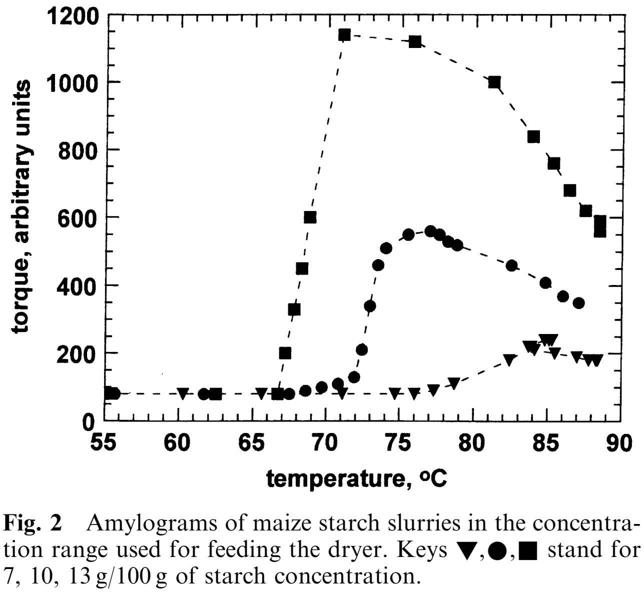

Fig. 2 Amylograms of maize starch slurries in the concentration range used for feeding the dryer. Keys ▼,●,■ stand for 7, 10, 13 g/100 g of starch concentration.

Macroscopical observations

Runs performed with slurries having 7 g/100 g solids are characterized by vigorous boiling in the pool between the drums. This is witnessed as a large number of vapor bubbles arriving and bursting at the free surface of the pool. An intense mixing and renewal of the liquid layers at the surface accompany this activity. With 10 g/100 g slurries boiling is drastically reduced. The material in the pool is now much more viscous resulting in poorer mixing and renewal of the free surface layers. The bubbles bursting at the free surface are less but vapor now escapes to the environment also from the sides of the pool where the liquid layers in contact with the drums once in a while bounce and depart from the drums. With a 13 g/100 g slurry there is almost no sign of boiling (bubbles) and the liquid layers on the free surface hardly move since the material in the pool is even more sluggish than with 10 g/100 g solids. A limited amount of vapor leaves the pool only from the contact line between the free surface and the drums. In summary, evaporation losses from the pool decrease substantially as the solids content of the slurry increases. Furthermore, in line with the observation of Vallous *et al.* (2002), it appears that the other (than the feed concentration) operating conditions of the dryer do not seriously affect the evaporation losses from the pool. For all the examined concentrations, at higher pool levels the free surface of the pool appears less disturbed by the boiling activity.

Vallous *et al.* (2002) working with 10 g/100 g starch slurries found that boiling does not remove more than 3% of the total moisture of the slurry in the pool regardless of the operating conditions of the dryer. Gavrielidou *et al.* (2002) based on measurements of temperature distribution across the pool concluded that this moisture loss comes chiefly from the material in contact with the drums since only there the material attains a temperature close to its boiling temperature; the rest of the pool being well below the boiling temperature. These authors further argued that at a position quite close to the gap this material gets finally partly solidified (due to drying) and adheres to the drums. It is only after this position that the material is carried over by the drum motion through the gap.

Because of the very high viscosity of the 13 g/100 g slurry, the free surface of the pool looks quite inhomogeneous. Around the point where the fresh cold feed is introduced (centerline of the pool) a low-viscosity region of ungelatinized material is formed while across the rest of the free surface small lumps of coherent gelatinized material alternate with regions of a homogeneous continuous phase. Moreover, there is no sign of movement of material on the longitudinal axis of the pool. With such a high solids content, the uniform introduction of the feed slurry over the entire length of the pool proved crucial in order to obtain a uniform final product.

In all the tests of the present study the gelatinized layers at the surface of the pool move from the sides of the pool towards its center. This is opposite to what is expected if the rotation of the drums rules the flow field of the material in the pool. When the layers from the sides of the pool reach the center they mix with the just-fed-in low-viscosity cold feed and together immerse vertically into the pool. The observed direction of surface motion might be viewed as a Marangoni (surface tension driven) flow but for the present slurries it is quite improbable that thermo-capillary forces can beat the significant viscous stresses at the surface.

Regarding the dry product sheets that are scraped off by the doctor knifes it is observed that feed slurries with higher solids content result in thicker and more humid products. For a 13 g/100 g slurry sometimes wetter zones appear randomly here and there on the product sheets. In all end products the granular shape of starch is completely absent. Instead, the sheets look like a composite medium in which irregular air pockets are randomly distributed inside the continuous solid phase. 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 viscoelasticity upon drying.

Temperature variation around the drum circumference

The temperature around the inside surface of the drum is quite constant but always a bit less than the temperature of the supplied steam. On the other hand, the temperature at the outside surface of the drums is not constant and is a result of a combination of all operating conditions.

Figure 3 displays the variation of the external temperature of the drums obtained during a full rotation (experimental conditions: steam pressure 7 bar, pool level 22 cm, drum speed 3 rpm, 10 g/100 g solids). For this particular drum speed the duration of a full rotation is 20 s; measurements start ($t=0$) at the doctor blades position. The outer surface temperature varies in a cyclic manner around the circumference as has already been demonstrated for single drum dryers by several workers, i.e., Vasseur and Loncin (1983), Daud and Armstrong (1987), Vasseur *et al.* (1991*a*), Bonazzi *et al.* (1996). Period I corresponds to the section of the rotation where no material is on the drums (from the doctor blades to the free surface of the liquid pool). Although the drums travel this section in less than 5 s, the temperature of the external surface of the drums manages to reach high values. This is so because the internal heat flux (steam→drum wall) is not succeeded by an equally high external

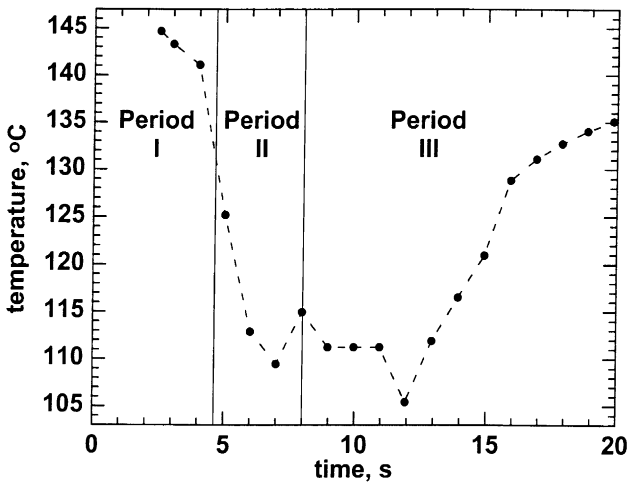

Fig. 3 Temperature variation around the external drum circumference. Experimental conditions: solids content 10 g/100 g, steam pressure 7 bar, pool level 22 cm, drum speed 3 rpm.

heat flux (drum wall→environment) and so heat is accumulated in the metallic body of the drums (Abchir *et al.*, 1988). There is evidence that external heat losses to the environment are no more than 10% of the internal heat flux (Vasseur *et al.*, 1992). The gradual lowering of temperature towards the end of Period I demonstrates heat transport in the angular direction. Daud and Armstrong (1987) also reported such 2-D effects.

As soon as the rotating drum dives into the pool, its external temperature drops rapidly (Period II). This is due to the increased external heat flux towards the material gelatinizing inside the pool. It was shown elsewhere (Gavrielidou *et al.*, 2002) that at the surface of the drums boiling of the adjacent liquid masses takes place and this is responsible for high heat exchange rates between the drums and the liquid in the pool. In this study the external temperature of the drum is always well above 100 °C so boiling can be indeed sustained. At the end of Period II (8th second) the temperature rises a little as the drums pass through the gap. According to Gavrielidou *et al.* (2002), very close to the gap boiling eventually ceases since the material in contact with the drums is already dry enough. Similar arguments were made by Daud and Armstrong (1987). In such a case the external heat flux will be reduced with a concomitant effect to increase the temperature of the drums. This is further confirmed by visually not observing any sign of boiling at the exit of the material through the gap.

The moment the rotating drum comes out of the pool its external temperature slightly drops (beginning of Period III) indicating a small rise in the external heat flux. This is attributed mostly to moisture evaporation from the applied film of material and to a much lesser extent to heat losses to the environment. The temperature at this part of the rotation remains invariable for a few seconds indicating a pretty constant external heat flux. This can be so as long as the water activity in the material adhered to the drums remains constant. Daud and Armstrong (1987) and Vasseur *et al.* (1991*a*,*b*) reported a similar flat temperature region in their single drum dryers.

The sudden temperature drop at the 12th second (corresponding to the lowest angular position of the drums) is probably due to some condensate accumulating at the inside bottom of the drums which reduces the internal heat flux (Abchir *et al.*, 1988). After this point the temperature climbs fast. It is quite probable that at this stage the material on the drums is already dry enough so its water activity falls significantly and so its temperature can rise above 100 °C. This would diminish the driving force for heat transport towards the product and so decrease the external heat flux. Unfortunately, sorption isotherms for the present slurries for temperatures above 100 °C could not be found in the literature to quantitatively confirm the above arguments. On the other hand, the gradual drying of the material leads to changes in the heat and mass transport properties as well as the thickness of the film which can also result in altering the external heat flux. The role of the parameters that govern film drying is quite complex and will be discussed further at a subsequent section. It is clearly shown in **Fig. 3** that the rate of temperature rise changes after the 15th second indicating a change in the drying process.

Effect of steam pressure vs. feed concentration

Temperatures presented in **Fig. 3** correspond to one set of operational parameters of the dryer. Changing any one of them modifies accordingly all the temperature readings around the drum. Thus, in order to study the influence of these parameters on drum operation a reference local temperature is chosen; the one measured on the bare metallic surface of the drums just after the doctor blades. The same location was also chosen by Vallous *et al.* (2002), who observed that temperatures measured at this spot fluctuate less with time than temperatures obtained at other locations around the drums where the material is present.

Steam pressure has a direct influence on drum temperature. Increasing the steam pressure increases the inner and, consequently, the outer temperature of the drums. This effect is clearly seen from **Fig. 4a** where runs conducted with a pool level of 18 cm and a speed of 5 rpm are presented. Clearly, the highest temperatures are observed for the more concentrated slurries. **Figure 4b** displays the variation of product moisture with steam pressure. Increasing the steam pressure generally makes the moisture to decrease unless it is already low enough (7 g/100 g slurry). Furthermore, the more the solids in the feed slurry the moister the final product. **Figure 4c** and **d** shows the dependence of the total mass flow rate and specific load of dry mass on steam pressure, respectively. The specific load of dry mass describes the quantity of material applied over the drums and it is considered as representative of film thickness (Vasseur *et al.*, 1991*b*; Vallous *et al.*, 2002). It must be noted that the mass flow rate is equal to the product of the specific load times the speed of rotation. Both quantities in

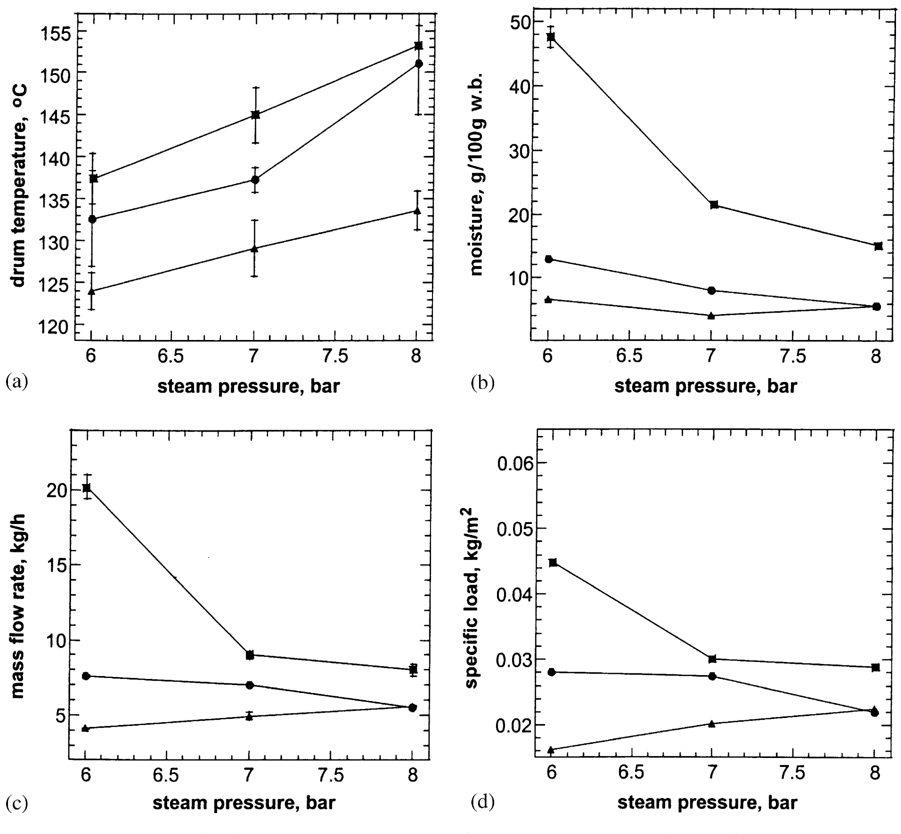

Fig. 4 Effect of steam pressure versus feed concentration on (a) drum temperature, (b) product moisture, (c) mass flow rate, and (d) specific load. Keys ▼,●,■ stand for 7, 10, 13 g/100 g of feed concentration, correspondingly. Other experimental conditions: pool level 18 cm, drum speed 5 rpm.

Fig. 4c and **d** bear similar trends with respect to steam pressure. However, an opposing trend is observed when comparing the more dilute slurry (7 g/100 g) to slurries with 10 and 13 g/100 g solids content. It is interesting that as steam pressure increases the deviation among the output variables in **Fig. 4b–d** tends to decline. Thus, at higher steam pressures the performance of the dryer is less sensitive to variations in feed concentration.

The higher drum temperatures for the more concentrated slurries in **Fig. 4a** (for fixed steam pressure) manifest a poorer external heat flux (drum → material). The fairly constant internal heat flux provided by the condensing steam inside the drums is only partly received by the material outside the drums, the other part is being used to rise the temperature of the drums which act as heat reservoirs. In this respect, two distinct contributions can be identified. One refers to the external heat flux from the drums to the material gelatinizing in the pool and the other to the material drying as a thin film after the gap. As regards the pool material, a reduction in heat flux might be expected due to the increased viscoelasticity of slurries with higher solids content which not only retards convective currents in the pool but also hinders the removal of vapor bubbles created by boiling on the drum surface (Gavrielidou *et al*., 2002).

Regarding film drying over the drums, at least three parameters must be taken into account: the transport properties, water activity and thickness of the material. A more moist starch gel has higher heat conductivity and moisture diffusivity (Saravacos *et al*., 1990). However, both properties are strongly related to the temperature and texture of the material. In particular, the role played by the progressively increasing porosity (void fraction) of the drying gel is intriguing; a higher porosity means lower heat conduction but higher mass diffusion. This is so because air has lower heat conductivity than any liquid or solid but moisture transfer by vapor diffusion is much faster than by liquid/solid diffusion (Saravacos *et al*., 1990). So the increased viscosity of the denser gels which enhances a more porous structure upon drying can either accelerate or decelerate transport phenomena in the film depending on the details of the system and therefore decrease or increase the drum temperature, respectively. Furthermore, as the film gets dryer its water activity drops (Vasseur *et al*., 1991*a*,*b*). This allows the temperature of the film to rise above its boiling temperature and attains values closer to the temperature of the drums and as a consequence the heat flux from the drums to the material diminishes. The parameter which is perhaps most significant is film thickness. With the more dense slurries thicker dry sheets are delivered. Heat flux is inversely proportional to film thickness and this may increase the drum temperature. On the whole, higher feed concentrations present a greater resistance to heat and mass transport. So, even if the drums are hotter the product removed by the doctor blades can be moister.

For feed concentrations of 10 and 13 g/100 g, rising the steam pressure causes a decrease in both product flow rate and specific load but the trend is reversed when the dryer is fed with a 7 g/100 g slurry. Vallous *et al*. (2002) working with the same dryer and 10 g/100 g slurries observed a monotonous drop in both quantities. However, Rosenthal and Sgarbieri (1992) producing dehydrated sweet corn pulp in a double drum dryer found the exit flow rate to decrease first and then increase with steam pressure in the range 3.5–5 bar.

At first glance **Fig. 4a–d** implies that the lower production rate and specific load as steam pressure increases for feed concentrations of 10 and 13 g/100 g may be due to the higher temperature of the drums which can remove more moisture from the product. One must realize, however, that the temperatures in **Fig. 4a** are indicative of the overall thermal condition of the drums (dictating their expansion or contraction). Thus, a higher drum temperature corresponds to a narrower gap between the drums which can result in a smaller throughput rate. On this account, the graphs of the dry mass flow rate *vs*. steam pressure (not shown) show similar trends with **Fig. 4c** so the impact of moisture removal is less important compared to the effect of gap narrowing in lowering the product flow rate and specific load.

Effect of pool level vs. feed concentration

The level of the pool dictates both the volume of the slurry in the pool and also the contact area of the slurry with the drums, so it is directly associated with the heat delivered by the drums. The pool level also determines the residence time of the material in the pool, which dictates the degree of starch gelatinization and therefore the viscosity of the slurry (Anastasiades *et al*., 2002). **Figure 5a** presents the effect of pool level on drum temperature. These tests are performed with a steam pressure of 7 bar and a drum speed of 5 rpm. Generally, the temperature drops as the pool level goes up. This may be attributed to a higher boiling load with pool level: the temperature of the drums fall because of a higher heat flux from the wall towards the material. However, the higher temperatures observed in **Fig. 5a** with the more concentrated slurries (for the same level) indicate that the rheological and transport properties of the material also influence the external heat flux of the drums. Thus, for a more concentrated slurry the ability to convect and conduct heat from the outside surface of the drums to the material is deteriorated and so the temperature of the drums rises given the finite heat capacity of the drum walls.

Figure 5b–d displays the variation of product moisture, mass flow rate and specific load with pool level for the same runs as in **Fig. 5a**. Moisture is not seriously affected by pool level for concentrations of 7 and 10 g/100 g. In this case, it appears that the thermal capacity of the dryer is high enough regardless of the other parameters so as to permit comparable drying of the material. This is different for a 13 g/100 g slurry where the moisture cannot be adequately removed when the pool level increases but an increasing trend is observed with pool level. Inspection of **Fig. 5c** and **d** indicates that the flow rate and film thickness may only

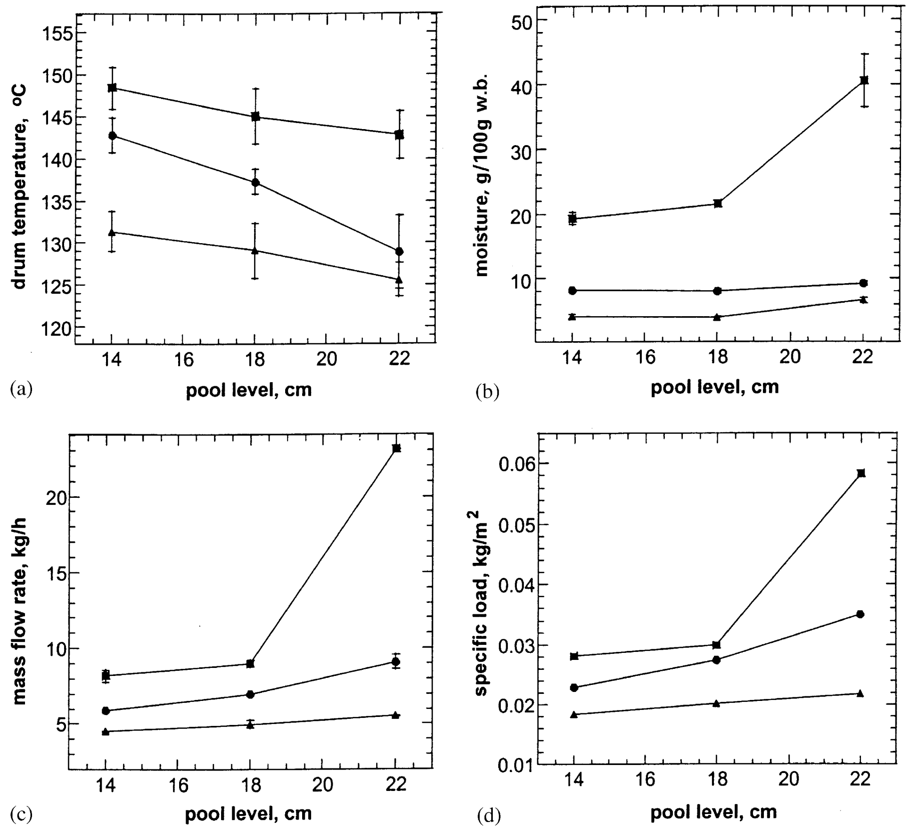

Fig. 5 Effect of pool level *vs.* feed concentration on (a) drum temperature, (b) product moisture, (c) mass flow rate, and (d) specific load. Keys ▼,●,■ stand for 7, 10, 13 g/100 g of feed concentration, correspondingly. Other experimental conditions: steam pressure 7 bar, drum speed 5 rpm.

be partly blamed for this. Vallous *et al.* (2002) ascribed the increasing trend of mass flow rate and film thickness mainly to gap widening (due to the lower drum temperatures). However, with more dense slurries, mass flow rate and film thickness reach higher values despite the higher drum temperatures. Evidently, feed concentration scores more than drum temperature in this respect.

From a practical point of view, at low pool levels, variations in feed concentration influence less the performance of the dryer. Vice versa, operation with a feed concentration of 7 g/100 g is less sensitive to variations of pool level. It is also interesting that for a 10 g/100 g slurry rising the pool level to 22 cm results in higher production rates with a virtually constant moisture.

Effect of drum speed vs. feed concentration

As the speed of rotation ascends the drum temperature descends, **Fig 6a**. The presented tests are conducted with a steam pressure of 7 bar and a pool level of 18 cm. Vallous *et al.* (2002) attributed this behavior to a combination of an increase in throughput rate and a decrease in film thickness and time available for drying. As throughput rate increases more heat is delivered by the drums whereas thinner films result in higher heat fluxes, too. In addition, shorter drying periods (larger rpm) are associated with lower drum temperatures since there is not enough time for heat build-up in the drum walls. These results are in qualitative agreement with the studies by Daud and Armstrong (1987), Vasseur *et al.* (1991*a*) and Trystram and Vasseur (1992).

In **Fig. 6b** the influence of drum rotation speed on the moisture of the final product is shown. A higher rotation speed generally causes wetter end products as also observed by other authors e.g., Daud and Armstrong (1987), Rosenthal and Sgabrieri (1992), Rodriguez *et al.* (1996*a*) and Vallous *et al.* (2002). It must be added though that the lower the feed concentration the smaller the influence of speed while at a concentration of 7 g/100 g practically no influence is observed because the material is too dry even for a 4 rpm speed.

Figures 6c and **d** displays the variation of mass flow rate and specific load with rotation speed. Here the dominance of concentration against speed of rotation is prominent. So for the higher feed concentrations (10 and 13 g/100 g) the present results show that the product outflow increases with speed. This is also what other studies concerning double drum dryers have shown e.g. Fritze (1973) and Rosenthal and Sgabrieri (1992). The respective film thickness is essentially invariant among the examined rotation speeds (considering the statistical significance of the determination). These results agree well with those reported by Vallous *et al.* (2001) for the same range of speeds and for a 10 g/100 g slurry. For a 7 g/100 g slurry though, while the mass flow rate is fairly constant the film thickness declines with speed. It suffices to state at this point that the varying rheological properties among the different feed concentrations are

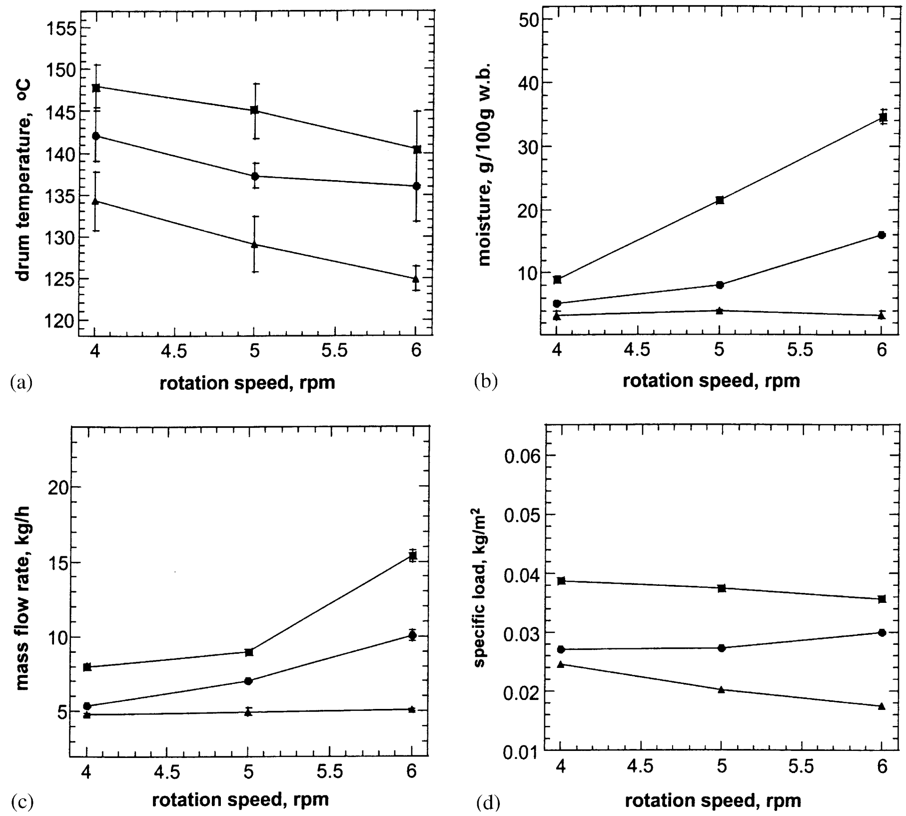

Fig. 6 Effect of drum speed *vs.* feed concentration on (a) drum temperature, (b) product moisture (c) mass flow rate, and (d) specific load. Keys ▼,●,■ stand for 7, 10, 13 g/100 g of feed concentration, correspondingly. Other experimental conditions: pool level 18 cm, steam pressure 7 bar.

to be blamed for this peculiar behavior (more about this later).

Correlation between product moisture and drum temperature

Figure 7 displays moisture values against drum temperatures for all the runs of this work. In all cases, the moisture of the product varies inversely proportional to the local drum temperature that is measured just after the blades. The displayed linear regression coefficients (significant to a confidence level of 95%) show a quite satisfactory linear correlation between temperature and moisture. Daud and Armstrong (1987) observed that the moisture content of the film is directly related to the temperature of the surface of the drum in Period II (**Fig. 3**). The effect of feed concentration is dominant. Data are gathered along distinct lines characteristic of each concentration despite the different values of the other operational variables of the dryer. This is another evidence that the external heat flux from the drums to the film (which depends strongly on the material's thickness and transport properties) vary chiefly with solids content. The significance of the correlation in **Fig. 7** for process control is apparent

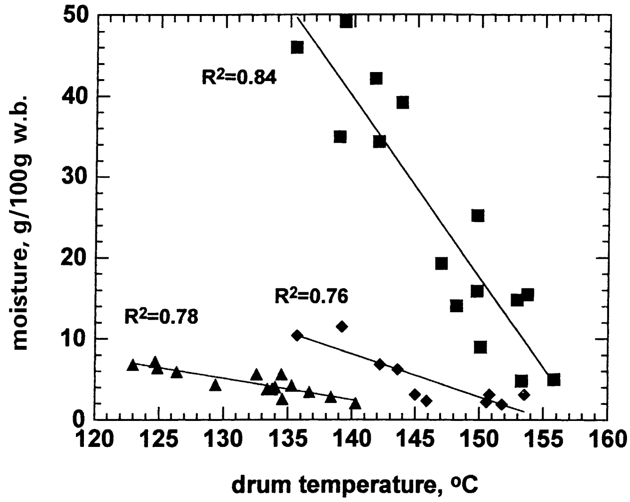

Fig. 7 Product moisture *vs.* drum temperature for all the employed experimental conditions. Keys ▼,●,■ stand for 7, 10, 13 g/100 g of feed concentration, correspondingly.

because of perturbations in moisture content (Moore, 1995; Rodriguez *et al.*, 1996*a,b*). In many cases, these problems are due to random fluctuations in the temperature of the two drums caused by the temporary malfunction of the steam trap of a drum or the accumulation of air or oil (from the steam generator) inside a drum. In order to understand the consequences of this ill condition and also to examine the interaction between the two unequally heated drums, experiments

Effect of different steam pressure in each drum

Industry frequently encounters problems regarding the quality of the output product of double drum dryers

Table 1 Effect of different steam pressures in each drum

	Drum A Pressure: 6 bar	Drum B Pressure: 8 bar	Both drums Pressure: 6 bar	Both drums Pressure: 8 bar
Temperature a (°C)	156.0 ± 0.5	166.0 ± 0.8	155.0 ± 0.5	167.8 ± 0.4
Temperature b (°C)	128 ± 0.5	138 ± 1.2	125.8 ± 1.0	152.4 ± 3.6
Moisture (g/100g w.b.)	9.9 ± 0.2	9.9 ± 0.2	15.7 ± 0.2	6.4 ± 0.2
Product flow rate (kg/h)	3.264 ± 0.138	3.564 ± 0.510	4.452 ± 0.18	2.816 ± 0.01
Specific load (kg/m^2)	0.012 ± 0.001	0.014 ± 0.002	0.016 ± 0.001	0.011 ± 0.000

Experimental conditions: pool level 22 cm, drum speed 4 rpm, solids content 10 g/100 g. (Temperature a: steady-state temperature before feeding; Temperature b: steady-state temperature after feeding.)

are conducted with the two drums heated at different steam pressures.

Table 1 presents the steady-state temperatures of the two drums before and after the introduction of the feed slurry using a steam pressure of 8 bar in the left drum and 6 bar in the right drum. Measurements are compared with results from experiments having the same steam pressure (6 or 8 bar) in both drums. It must be stressed that the temperature of the drums before the introduction of the slurry is pretty constant around their circumference whereas when the material is on the drums the temperature measurements refer, as before, to the specific location just after the doctor blades.

Before the introduction of the slurry the temperatures of the two drums are quite close to the isothermal values. The temperature of the hot drum appears to deviate a bit more from the isothermal case due to larger heat losses to the surroundings. When the slurry is fed in, all the temperatures get lower. Again the deviation of the hot drum is larger. This is so because the drum with the elevated temperature is the major energy supplier to the material in the pool and over the drums. The slight increase of the cold drum temperature with respect to the isothermal case indicates that the external heat flux from the cold drum to the starch slurry is now less so some more heat accumulates to the body of this drum.

Regarding the product mass flow rate and moisture, the nonisothermal experiment gives values between those of the isothermal runs. What is perhaps more interesting is that these values are the same for the two drums despite the different steam pressures. This observation suggests that film application over the drums at the gap is not governed by the different thermal condition of each drum but by phenomena occurring locally at the region of the gap. Recalling **Fig. 3**, it is likely that both drums attain comparably low temperatures at the region of the gap. If in addition one considers the strong mixing effect ensuing from the high degree of compression of the material as it moves through the gap it is possible that the material across the gap width is essentially homogeneous and isothermal with uniform rheological properties. It is these properties that determine the splitting of the exiting material into two equal films, one for every drum, as observed in **Table 1**. The equal moisture content of the products from the two drums is probably due to the fact that the water content of the material adhered to the drums at the gap is already low enough (Gavrielidou *et al.*, 2002). So from an energetic point of view it seems that the drums have only a small thermal duty for drying the material after the gap and the slow speed of rotation in this occasion allows sufficient drying of the film in both drums. From a practical standpoint, variations in the thermal condition of one drum appear to influence the operation of the whole dryer and affect the product flow rate and moisture content in both drums.

Effect of preheating the feed slurry

Operating the dryer with a feed concentration of 13 g/100 g gives higher throughput rates and this has a paramount economical importance. In this case, however, the product sheets are often of poor quality because they exhibit several wetter spots randomly distributed across their surface. A probable cause for this may be that the slurry gelatinizing in the pool is quite inhomogeneous since the hot already gelatinized material does not spontaneously mix with the just-fed-in cold starch suspension. A way to diminish the temperature inhomogeneity in the pool is to preheat the starch suspension before it is fed to the dryer. Apparently, the preheating must be kept below the gelatinization temperature to avoid plugging of pipelines. In some runs of this work the starch suspension is first preheated to 50 °C and then it is fed to the dryer. The preheating tank is closed at the top so evaporation losses at this stage are limited. Results for the mass flow rate and moisture content of the end product are shown in **Table 2** for experiments with and without a preheated feed. No significant difference is observed in the product macroscopical characteristics between the two experiments although the preheated feed clearly yields a much better mixing of the liquid masses in the pool. So it is not the inhomogeneity in the pool that should be blamed for the problems of inadequate or uneven drying but rather the thickness and transport properties of the film combined perhaps with zones of uneven initial deposition of the material over the drums. The situation improves a little with smaller rotation speeds and lower pool levels. Such wet zones were also experienced by Rodriguez *et al.* (1996a) and were attributed to minor local deformations of the dryer's surface.

It must be added here that for the runs in **Tables 1** and **2** a new lot of starch is used, other than in all previous runs, with a quite different rheological behavior. This has a direct consequence to the values of all output variables but does not invalidate the comparisons made among the elements of these Tables.

Table 2 Effect of preheating the feed slurry

	Preheated starch suspension (50 °C)	Nonpreheated starch suspension (15 °C)
Temperature b (°C)	148.3 ± 1.9	149.0 ± 1.3
Moisture (g/100 g w.b.)	14.7 ± 0.9	15.0 ± 1.3
Product flow rate (kg/h)	7.26 ± 0.08	6.97 ± 0.14
Specific load (kg/m^2)	0.015 ± 0.000	0.015 ± 0.000

Experimental conditions: steam pressure 7 bar, pool level 18 cm, drum speed 5 rpm, solids content 13 g/100 g. (Temperature b: steady-state temperature after feeding.)

Material application on the drums surface

On the basis of all the above evidence, an effort is made to delineate the physical picture of material take-up by the drums in the form of thin films. Vallous *et al.* (2002) presented an approximate mathematical analysis of the roll-coating problem in a double drum dryer valid for very viscous gelatinized slurries. Their analysis predicted that, if only viscous effects are considered, the film thickness of the material spread over the drums is proportional to the width of the gap. In **Figs 4–6**, however, it is observed that the mass flow rate and thickness of the dry product increase with solids content of the feed slurry despite the gap being smaller (higher drum temperatures). If this is further combined with the opposing trends observed with a 7 g/100 g slurry, it appears that the material carry over by the drums is a result of a more complex behavior than the one addressed by Vallous *et al.* (2002).

Fritze (1973) working with starch concentrations above 15 g/100 g proposed a physical model for the product take-up by the drums which calls for a competition between the adhesion forces between the drum surface and the product (and also the cohesion forces in the product itself) and the shear stresses imposed by the motion of the drums. When the adhesion forces exceed the inherent molecular forces of the product then the drums shear off the product. These adhesion forces increase with product viscosity, which, in turn, increases with solids content and this explains why the production rate increases with feed concentration (Fritze, 1973). In this work we have also observed a significant increase in adhesion with solids content. Qualitatively speaking, for 7 g/100 g solids adhesion is hardly noticed, for 10 g/100 g it is appreciable while for 13 g/100 g it is substantial. Nevertheless, it is questionable whether this increase in adhesion alone can beat the opposite effect of gap narrowing with the denser slurries (higher drum temperatures) and yield the observed higher production rates. Instead we believe that the explanation of the peculiar behavior among the different slurries must incorporate their strongly varying viscoelastic properties. Gelatinized maize starch suspensions above 7 g/100 g w/w form closely packed systems with appreciable viscosities and elasticities which are governed by the rigidity of the swollen particles that can deform and compress under strain (Evans and Haisman, 1979; Steeneken, 1989; Evans and Lips, 1992). Even within such a limited range of concentrations (7–13 g/100 g) starch slurries present considerably different viscosities (**Fig. 2**; Xu and Raphaelides, 1998), their resistance to uniaxial compression differs by several times (Christianson and Bagley, 1990) and they exhibit a varying yield stress and elastic response to shearing (Evans and Haisman, 1979; Steeneken, 1989).

Keeping the above in mind, **Fig. 8** presents a simplified schematic impression of what may occur at the region of the gap with slurries of different concentrations (and therefore different viscoelastic properties) but all adhering adequately to the drums (i.e. 10 and 13 g/100 g solids). For a higher viscosity (13 g/100 g) the drums are surrounded by thicker momentum boundary layers which intersect at a location farther up from the gap than the thinner boundary layers of the less viscous material (10 g/100 g). At the point of intersection the material is subjected to two forces. A shear force which tries to drag the material towards the gap but because of the converging wedge geometry creates also a backflow of material upstream of the intersection (Coyle *et al.*, 1986; Papanastasiou, 1994), and also a compression force that deforms the swollen starch particles in order to squeeze them in the progressively narrower wedge. An analysis by Daud (1986) concerning the calendering of a power law fluid in a single drum dryer has also shown that at the bottom of the pool some material may not pass through the gap but moves backwards (in the opposite direction of the main flow in the pool). For higher viscosities (solids content) the back upward flow of the slurry is greatly hampered and as a result more material is compressed and dragged down through the gap. Since the compression force exerted by the drums is practically infinite with respect to the rigidity of the swollen starch particles, their resistance to compression is insignificant for all concentrations. Thus, it is chiefly the viscosity of the pool material that determines the flow rate through the gap by dictating the size of the boundary layers and the capacity for backflow. For a fixed feed concentration the drop of viscosity at higher temperatures has a parallel effect with gap narrowing in reducing mass flow rate. Furthermore, the film of material applied after the gap is thicker for the denser slurries not only because of the higher (dry) flow rate but

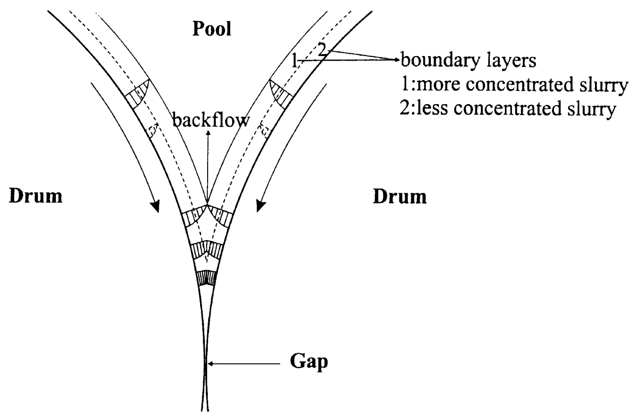

Fig. 8 Qualitative schematic representation of material carry-over at the region of the gap for two different feed concentrations.

to some extent also because of the larger swelling after the elastic stresses imposed by the drums are released. A more complete explanation may also take into account the competition between film inflation and film shrinkage in the boiling-type dehydration of the material at the region of the gap (Vallous *et al.*, 2002).

With the considerably less viscous 7 g/100 g slurry the adhesion with the drum is so weak that the boundary layers around the drums are rather too small and may not intersect. The possibility that the boundary layers do not form at all (given the low speeds of the drums) is small since then no material would practically adhere and dry as a film on the drums. Due to the small boundary layers enhanced by the wider gaps (due to the lower drum temperatures), most of the material passing through the gap flows chiefly under its own weight in a gravity-driven-type of flow down a converging channel (Papanastasiou, 1994). Such a behavior is constantly observed when hot water is poured between the hot drums to clean the dryer at the end of an experiment. So for a 7 g/100 g slurry when the temperature of the drums rises the slurry in the pool gets even less viscous and this can explain the increasing trends in **Fig. 4c** and **d** despite the narrower gap. Furthermore, a gravity-driven flow between the two drums, being independent of the rotation speed, may also explain why the mass flow rate is fairly constant in **Fig. 6c** and as a consequence the film thickness declines with speed in **Fig. 6d**.

Conclusions

Among the examined input variables (steam pressure, pool level, rotation speed and feed concentration) the concentration of the feed slurry appears to be more significant for the performance of the dryer. The effect of varying the steam pressure, pool level and rotation speed on the output variables is different at different feed concentrations. For a 7 g/100 g feed slurry the effect is marginal while it becomes more pronounced as the concentration of the feed slurry increases. So for a 13 g/100 g slurry the product moisture, mass flow rate and specific load are the greatest regardless of the values of the other input variables. However, operating the dryer with a 13 g/100 g feed slurry often results in product sheets of uneven moisture. On the other hand, the less concentrated films dry easier but at much smaller product outflows. So from a practical point of view the 10 g/100 g slurry seems a reasonable compromise.

Preheating the feed slurry before its introduction to the dryer does not seem to improve the performance of the dryer. In addition, experiments with different steam pressures in the two drums indicate that the application of material as a film over the drums surface (at the gap) is governed by the rheological properties of the material right at the region of the gap. This information combined with the notion of thick momentum boundary layers surrounding the drums has been employed to explain the considerable increase in mass flow rate (and specific load) when the slurry solids content increases at least above 10 g/100 g. This approach is also in line with the variation of mass flow rate with respect to the other input variables. The behavior of the dryer with a 7 g/100 g slurry is quite different and appears to be satisfactorily described by a gravity-driven free flow of the material in the pool between the very thin—in this case—boundary layers around the drums.

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