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Journal of Food Engineering **6** (1987) 423–444

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(Received 13 May 1986; revised version received 21 January 1987; accepted 11 February 1987)

ABSTRACT

Temperature and pressure inside a twin screw pilot-scale extruder (Clextral BC 45) were measured. The product — maize starch, and screw configuration — transport elements and one reverse screw element before the die, were chosen to be very simple. Axial profiles were determined: the increase in temperature up to 150–200°C is linked with the position of the reverse screw element, the increase in pressure up to 50–80 bar was mainly due to the die. Of the process variables studied, water content and feed rate had the greatest effect. When feed rate and screw speed were changed simultaneously in order to keep the fill fraction constant, the temperature remained steady whereas pressure at the die increased, changing the equilibrium point of the machine.

Interpretation of these observations is suggested in terms of conduction, convection, friction, shear and pressure build-up in polymer flow.

INTRODUCTION

Due to its unequalled versatility, extrusion-cooking has led to many applications (Linko *et al.*, 1981; Harper, 1981; Cost 91, Subgroup 1, 1984; Harper and Jansen, 1985). One of its most important fields is starch conversion. Many publications describing this use examine the influence of several extrusion variables (machine operating conditions and water content) on the physical structure and macromolecular state or functional properties of the product. Some recent papers report experimental investigations (Owusu-Ansah *et al.*, 1982, 1983; Gomez

Journal of Food Engineering 0260-8774/87/$03.50 —

and Aguilera 1983; Launay and Lisch, 1983) and others attempt to predict product changes by a 'black box' model (Meuser *et al.*, 1982; Olkku and Hagqvist, 1983; Kervinen *et al.*, 1985). Such studies have contributed notably to the development of extrusion-cooking technology but, still, there is little basic comprehension of the process even if its importance is generally recognized.

Comprehension involves establishing relationships based on internal process variables (pressure, temperature, shear, residence time) between controlled extrusion variables and product properties. In such an approach, Colonna and Mercier (1983a) have shown that extrusion cooking of manioc starch led to a degradation of macromolecular amylose and amylopectin by chain splitting. Davidson *et al.* (1984) have observed the same effect of degradation in wheat starch in a single screw extruder. Colonna *et al.* (1983b) using a longitudinally split barrel twin screw extruder, operating with a simple screw configuration, identified four functional zones. First, from the inlet to the reverse screw element, where the starch fills a small part of screw chambers, starch granules remain in a solid state and undergo little conversion (zone A); second, in the last direct flight, material accumulates and melts (zone B); third, in the reverse screw element, molten starch is sheared and significant macromolecular degradation occurs (zone C); the last zone (zone D), between the screw head and die, does not play a major role in starch conversion.

To develop this approach requires the quantification of internal conditions of processing, i.e. determining residence time distributions and temperature, pressure and shear fields within the extruder. Residence time distribution in twin screw extruders similar to the one used in this study has been thoroughly examined (Olkku *et al.*, 1980a; Mosso *et al.*, 1982; Colonna *et al.*, 1983b; Mange and Gelus, 1984). In the case of pressure and temperature, published studies do not refer to simple experimental conditions (substrate and screw configuration) which would provide comprehension rather than observation. Olkku *et al.* (1980b), Meuser *et al.* (1982) measured pressure and temperature at the die but their studies were neither systematic nor directed to this subject. Some other investigations in this field are more complete: Mosso *et al.* (1982) have studied the influence of machine operating conditions but with a complex substrate; Fletcher *et al.* (1984), Imeson *et al.* (1985) Senouci and Smith (1986) have published some axial profiles, but with a complex screw configuration.

The aim of the present work was to carry out and to analyse systematic temperature and pressure measurements. Maize starch was chosen as a model substrate, and a longitudinally instrumented twin screw extruder was used with a simple screw configuration so that the axial profiles of temperature and pressure may be explained in relation to the product conversion and the screw configuration. Secondly, extrusion conditions were varied in order to test their separate effect on pressure and temperature. These data provide information relevant to the working of a twin screw extruder and are also necessary for the future development of a model of the relationship between controllable extrusion variables and internal processing conditions.

MATERIALS AND METHODS

Starch

Commercial maize starch Rofec was purchased from Roquette, Lestrem, France. Its normal moisture content is 13% (wet-weight basis).

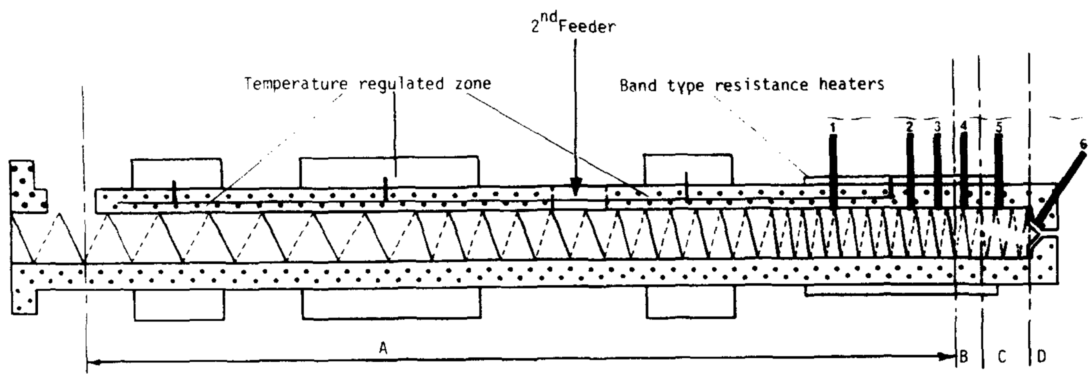
Extruder

A twin-screw extruder, Clextral BC 45, was used. The barrel is 1 m long, divided into 4 sections heated by induction or by band-type resistance heaters, and cooled by water circulation (Fig. 1). The usual adjustments can be made to feed rate, screw speed, barrel temperature and water addition rate; motor current may be measured; the pressure on the screw head can be measured by means of a pressure sensor mounted on the screw shaft thrust blocks. A second feeder can be connected to the middle of the barrel to enable the machine to work with a short barrel (50 cm long) configuration.

The screw consists of two different modules of different lengths (100 mm and 50 mm) and decreasing flight pitch, from feeder to die (Fig. 1); it was terminated by a reverse screw element except when stated otherwise. This element has 6 mm wide straight gaps for leakage flow. The die is composed of two, 30 mm long, 4 mm diameter, cylindrical tubes.

The barrel of the extruder was modified to accept probes in holes in the terminal section, as Colonna *et al.* (1983b) have shown the importance of this section in product conversion. The five flush mounted probe holes are located at (Fig. 2):

— the space between screwhead and die,
— the mid-point of the reverse screw element (noted RSE),
— the mid-point of the last direct flight before the RSE (LNF),
— the mid-point of the third direct flight before the RSE (3rd NF),
— the mid-point of the fifth direct flight before the RSE (5th NF).



Pitch (mm) :	20	10	10	10	10	10	5	5	5	10	5
Length(mm) :	50	50	50	35	35	25	25	15	15	15	-15

ø 4 mm

Screw Configuration (Total Length : 1m)

Fig. 1. Axial section of the extrusion cooker (zone A: direct flights; zone B: last direct flights (LDF); zone C: reverse screw element (RSE); zone D: die).

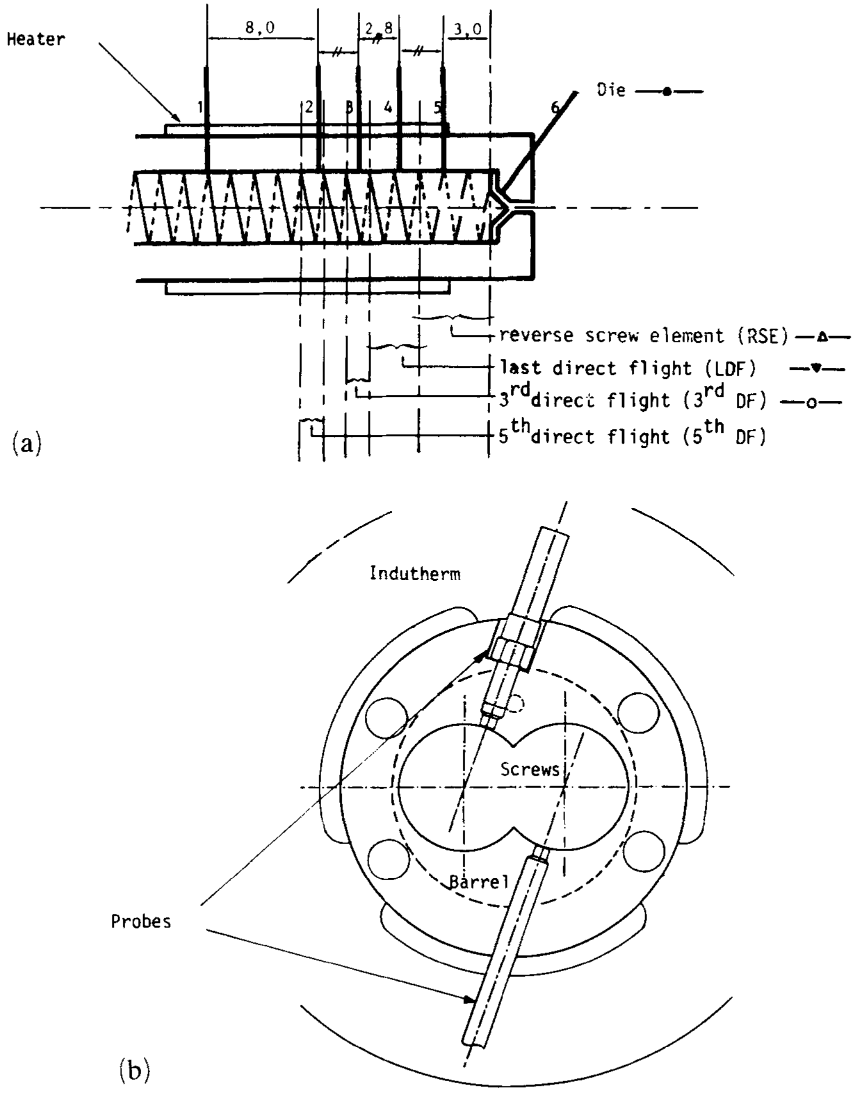
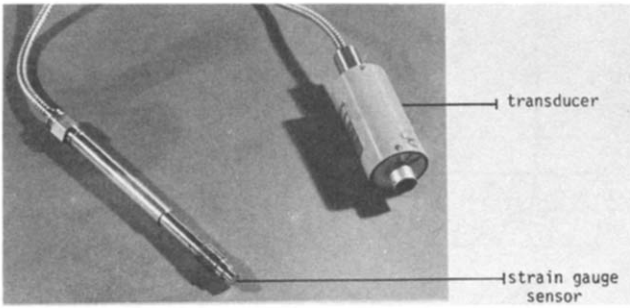


Fig. 2. (a) Longitudinal position of probes (dimensions in cm). (b) Radial position of probes.

Probes

The pressure probes are strain gauge sensors (Dynisco PT 462 E) (Fig. 3). Their precision is 1% of the measuring range of 0–345 bar. It was confirmed during calibration trials that the thermal drift did not exceed 3 bar in the temperatures used (150–200°C) and no interference between



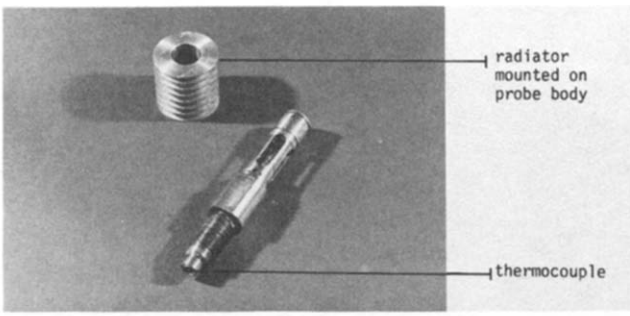


Fig. 3. Pressure and temperature probes.

the pressure signal and the heating systems occurred provided the transducers and induction heaters were more than 40 cm apart. A combined probe TPT463E, which also indicates temperature was used for pressure measurement at the die.

The temperature probes, manufactured by CEMEF (Ecole des Mines de Paris, 06560 Valbonne, France) are Chromel–Alumel thermocouples (type K) mounted in a heat-resistant and electrically-insulating polyimide resin. A radiator is fitted to the probe body to dissipate heat from the barrel; this radiator and the heat-insulating resin are designed to avoid measuring the temperature of the barrel instead of the temperature of the product (Fig. 3).

Signal recording

All the probe signals are passed on a 12 channel, hybrid, programmable printer YEW 3087 by means of armoured cables. The 12 channels are scanned at five second intervals. Thermocouple voltages are measured by the recorder. Before being recorded, pressure signals are converted to 4–20 mA current by home-made conversion cards based on the integrated circuit Burr Brown XTR 100; these cards were calibrated using a pressure indicator Dynisco ER 478. Extrusion conditions, i.e. the set temperature of each heated section, solid feed rate, screw speed, and also the motor current and thrust block pressure are recorded on the YEW 3087 allowing useful comparison with measured signals. Conventional chart recorders can also be attached when necessary.

Operating method

The standard extrusion conditions used were:

— barrel temperature: 1st heating zone: 40°C; 2nd heating zone: 80°C; 3rd heating zone: 140°C; final heating zone: 180°C (Fig. 1);
— screw rotation speed: 210 rpm;
— feed rate: 30 kg h^{-1};
— water added: 10% (i.e. total moisture content: 21% on wet weight basis);
— reverse screw element in final position (Fig. 1).

Changes in these variables were made one at a time over the following ranges:

— barrel temperature: in 3rd heating zone: 100–140°C; in final heating zone: 120–180°C;
— screw rotation speed: 130–250 rpm;
— feed rate: 20–50 kg h^{-1};
— water added: 5–30% (i.e. total moisture content range of 17–33% on wet basis);
— barrel length: two different lengths (1 m and 0·5 m) of barrel have been tested in order to give more information on the working of zone A;
— screw configuration: an experiment was carried out with a different screw configuration from the standard one: a forward screw element was placed in the terminal position following a reverse screw element in order to determine the specific effect of the reverse element.

Variables not investigated in the experiment were held at the reference value.

Temperature and pressure were the average, over a five minute interval, of the chart recordings taken when the extruder was running steadily at the desired operating conditions. Data spread around the mean value is indicated by range bar on the graphical presentation of the results. The extruder was judged to be at a steady state when the measured variables — motor current and the controlled temperatures — attained steady values, which took about 10 minutes; the machine is then said to have reached an equilibrium point. Flow rate was determined by weighing the extruded product over a time interval (about 5 min), without taking into account the water evaporated after the die.

RESULTS AND DISCUSSION

Quality of measured signals

A typical record of temperature and pressure is shown in Fig. 4. The left-hand side shows unstable working conditions characterized by wide fluctuations in pressure and temperature. When normal conditions are established (right-hand side of the chart) a periodic signal with smaller fluctuations is observed from which an average value is derived. The amplitude of these fluctuations being 6 bar for pressure and 3°C for temperature, the measurement precision is about ± 15% and ± 2% respectively. It has been verified that the apparent period of this signal corresponds to the time necessary for one screw revolution.

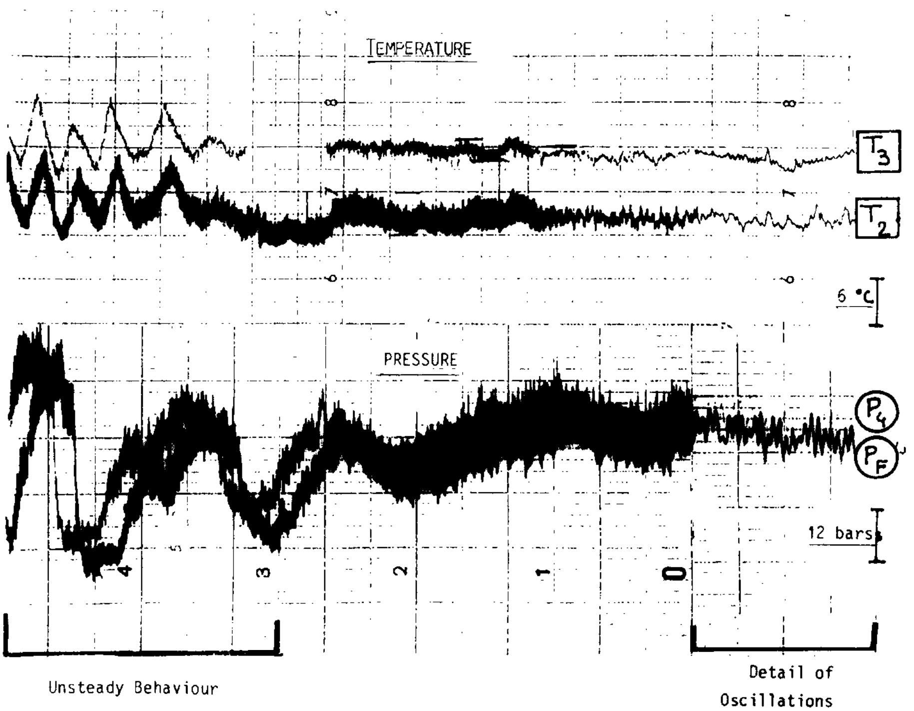


Fig. 4. Example of temperature and pressure records.

TABLE 1
Repeatability of Results

No of trial[a]	*Operating conditions*				*Measurements*		
	Temperature of barrel at the die end (°C)	*Screw speed (rpm)*	*Feed rate (kg h^{-1})*	*Added water (% wsb)*	*Position of probes*	*Temperature (°C)*	*Pressure (bar)*
					End of zone A	212–214	—
1	176–178	210	29.7	10.1	LDF: zone B	185–187	23–27
					RSE: zone C	190–193	—
					Die: zone D	—	36–48
					End of zone A	166–170	—
2	172–175	210	28	10	LDF: zone B	170–174	16–20
					RSE: zone C	180–183	39–51
					Die: zone D	152	44–50
					End of zone A	190–196	—
3	170–173	210	29·5	10	LDF: zone B	172–180	25–30
					RSE: zone C	184–186	47–62
					Die: zone D	168–170	40–60

[a]These trials were carried out with the long barrel and normal screw configuration.

The repeatability of the measurements was checked by repeating the same standard operating conditions, with a precision of ±4% on each extrusion variable, on different occasions (Table 1). A major cause for the scatter might be the difficulty of ensuring exactly the same feed rate on different occasions: starch packing and bridging in the hopper causes variations to the extent that the sum of the rate of water addition and the mass flow rate at the feeder agrees with total feed rate at the die within ±4%. Results showed that the temperature of the product varied between 170 and 187°C in zone B, 180 and 193°C in zone C, 152 and 170°C in zone D. These variations represented a relative error of ±5% which was wider than the above but still acceptable. The pressure was 16–30 bar in zone B, 39–62 bar in zone C, 36–60 bar in zone D. The differences in temperature in zone A were not insignificant (about 50°C); this variation might be due to the fact that the temperature probes only measured the product temperature at the inner surface of the barrel; furthermore, the starch is still granular in zone A, so thermal contact between the probe and the product is not as good as in subsequent zones where starch is molten.

Longitudinal profiles of temperature and pressure

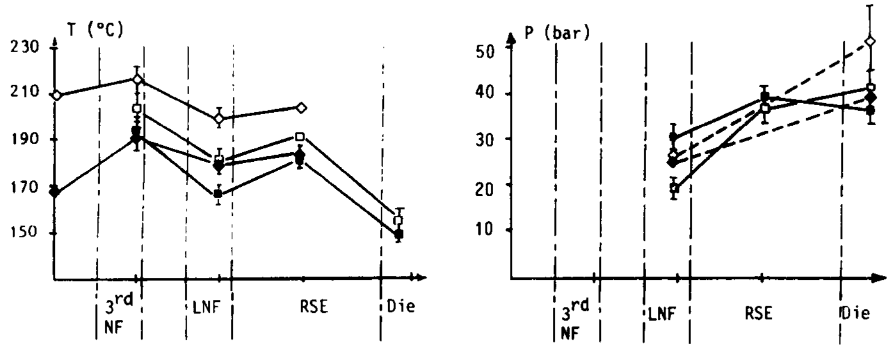
Results

Longitudinal profiles were drawn by plotting temperature or pressure as a function of axial distance z between the fifth direct flight and the die (Figs 5, 6 and 7). They are of the same shape even when the added water rate is changed.

For a long (1 m) barrel with a normal screw configuration (Fig. 5), the temperature reaches a maximum in the third direct flight (3rd NF) of 190–220°C, then decreases to 170–200°C at the LNF, increases slightly to 180–200°C at the RSE and finally drops to near 150°C at the die. Despite the small number of experimental points, it seems established that the pressure increases by 10–20 bar between LNF and RSE, to reach its maximum of 40 bar, then decreases slightly at the die to 30 bar.

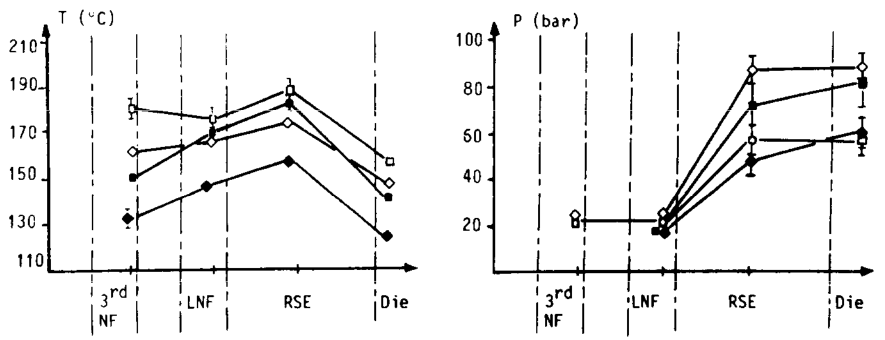
With a short (0·5 m) barrel (Fig. 6), some differences may be observed from the results obtained with the long one, for the same screw configuration:

- the temperature in the 3rd NF is lower (130–180°C) and rises steadily up to 150–190°C at the RSE;
- pressure remains below 20 bar before the LNF and the measurement may not be accurate for pressure at such values; however, the pressure build-up between the LNF and the RSE is steeper and reaches about 60 bar at its highest value;



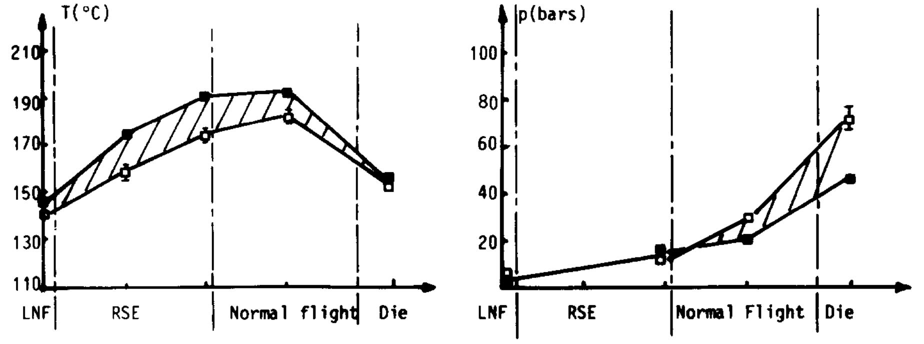
Barrel temperature (°C)	Screw speed (rpm)	Feed rate ($kg\ h^{-1}$)	Water added (%)	Symbol
180	210	30	5	—◇—
160	210	30	10	—◆—
180	210	40	10	—■—
180	210	20	10	—□—

Fig. 5. Product pressure and temperature profiles for long barrel.



Barrel temperature (°C)	Screw speed (rpm)	Feed rate ($kg\ h^{-1}$)	Water added (%)	Symbol
145	210	25	13	—◆—
145	210	26	5	—■—
155	210	30	10	—□—
145	210	50	10	—◇—

Fig. 6. Product pressure and temperature profiles for short barrel.



Barrel temperature (°C)	Screw speed (rpm)	Feed rate (kg h^{-1})	Water added (%)	Symbol
135	200	50	10	—□—
145	240	25	10	—■—

Fig. 7. Product pressure and temperature profiles obtained with direct flight screw in terminal position.

— the motor current is much less (15–20 A) with the short than with the longer barrel (30–40 A).

For the tests with the reverse screw element located before a direct flight element with the short barrel only boundary profiles have been drawn (Fig. 7). Temperature profiles have the same shape as those obtained with the normal screw configuration. Temperature increases by about 40°C in the RSE and remains constant in the following direct flights. Pressure at the die reaches the same level as in the case of the normal screw configuration (40–60 bar) but the profiles clearly show that pressure increases only at the die. The reverse screw element does not itself produce significant changes in pressure.

Discussion

It may be noted first that the values of temperature and pressure observed are similar to those found in other studies (Olkku *et al.*, 1980b; Meuser *et al.*, 1982) even if the pressures are less than those reported (50–100 bar). This difference can be explained by the die geometry: a simple physical model of polymer flow through a tube shows that pressure depends greatly on diameter. The shape of the profiles confirms the usefulness of the division of the extruder into four working zones, as proposed by Colonna *et al.* (1983b), in the case of extrusion-cooking of starch with a simple screw configuration (reverse screw element in terminal position).

(a) Zone A (normal flights). The difference in the product temperature at the end of zone A (3rd direct flight) between the experiments with the long and the short barrel is partly explained by the difference of barrel temperatures (160–180°C in Fig. 5, 145–155°C in Fig. 6). However thermal convection is not the only explanation as the product temperature is greater than that of the barrel; the balance of energy is probably supplied to the product by friction since the starch is still solid in zone A and starch granules rub on the barrel surface as they pass under the edge of the screw flight. So the longer is the conveying section, the higher is the temperature reached at the end of zone A. This would also explain the greater power consumption of the long barrel extruder.

Since the screws are not completely filled, the product pressure is approximately zero and oscillations in the pressure signal are due to the edge of the screw flight passing over the sensor.

(b) Zone B (last normal flight). The measurement here is more truly representative of the real temperature of the product because at LNF, starch granules accumulate, mix and melt. The layer overheated by friction in the case of the long barrel disappears and the temperature becomes more uniform as the product enters zone B: the temperature decreases in the long barrel but increases in the short barrel so that the difference existing in zone A between this long and short barrel condition is reduced.

The pressure increase in zone B corresponds to accumulation of starch as described by Colonna *et al.* (1983b) and as explained later on (zone D).

(c) Zone C (reverse screw element — RSE). Results are the same for long and short barrels. Temperature increases considerably as the product passes through RSE (Fig. 7) and exceeds the barrel temperature whatever the screw configuration, no doubt due to high shear dissipation in the molten starch.

When the reverse screw element is placed before a direct flight element, the product pressure does not vary much (Fig. 7) as the product flows through the RSE. So, for standard screw configuration, pressure increase is not due to the presence of RSE.

(d) Zone D (die). At present, no explanation can be offered for the temperature drop at the die: it may be due to a real physical

phenomenon (cooling by conduction from ambient air) or relate to the measurement itself (the probe at the die was of a different design from the others).

Pressure here is due to the resistance to starch flow through the die (Fig. 7). In the case of the standard screw configuration, this high die pressure is transmitted through the RSE (across which the pressure drop is small as explained above) to the end of the direct screw element (zone B). In this zone, the pressure necessary for the product to flow through the die is generated by the action of the screws on a given length of molten starch.

Since these profiles confirm the usefulness of the conceptual division into four zones, it is interesting to see how pressure and temperature vary in each section with extrusion conditions in the case of a standard screw configuration.

Change of extrusion variables

Results

(a) Variations in the barrel temperature in the final heating zone do not significantly affect product temperature (180–200°C) or pressure (40–50 bar) in any of the zones studied provided that these variations are small (Fig. 8). However, when the barrel temperature is much lower (120°C) the temperature of the product also decreases to the same extent (140°C). This is particularly so in zone A where the product temperature also drops to 120°C; such a change of barrel temperature produces an increase of the pressure at the die to 60–70 bar.

(b) No clear influence of screw speed on temperature or pressure can be noted (Fig. 9), in the case of either the long barrel (continuous

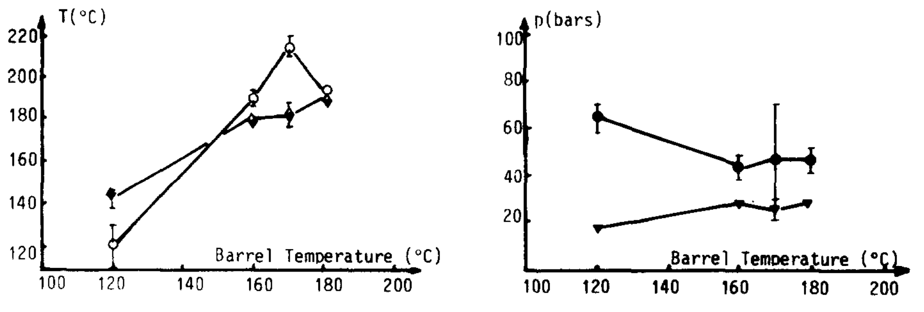


Fig. 8. Change in product pressure and temperature with barrel heating temperature (End of zone A: —○—; zone B: —▼—; zone C: —△—; zone D: —●—).

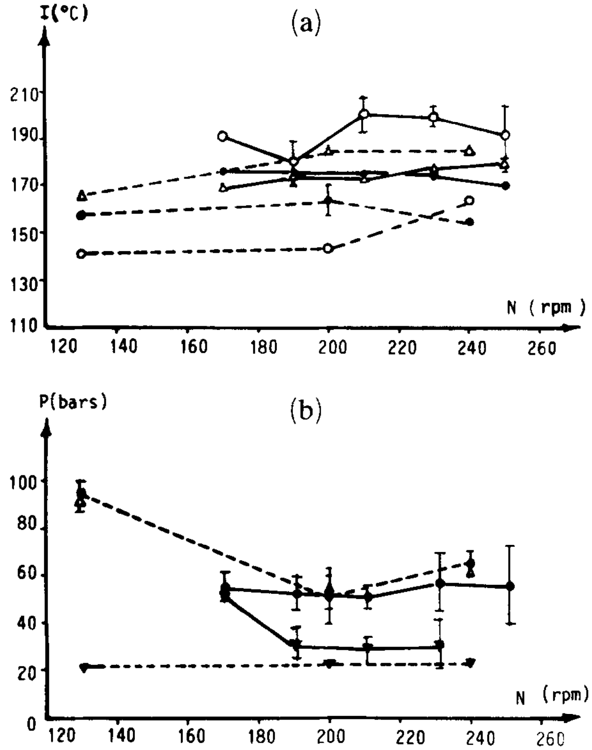


Fig. 9. Change in product pressure and temperature with screw speed (long barrel: ——; short barrel: - - -). (End of zone A: —○—; zone B: —▼—; zone C: —△—; zone D: —●—).

line) or the short barrel (dashed line). Only a small increase in temperature (10–15°C) in zone C, and a small pressure drop (20 bar) in zone C and D can be noted in the range of screw speed explored (130–250 rpm).

(c) The influence of feed rate was first studied with constant screw speed. In zone A, temperature drops (40°C) when the feed rate rises in the case of both barrel lengths whereas the decrease is smaller (10°C) in the other zones (Fig. 10). The pressure in zone B is not much affected by changes of feed rate whereas it increases considerably (30–40 bar) in zone C and D.

(d) When feed rate Q and screw speed N are changed simultaneously in order to keep Q/N constant, the temperature remains constant in all zones at each value of Q/N (Fig. 11). When Q/N is changed (dashed line $Q/N=$ 24%, continuous line $Q/N=17\%$) marked change in temperature (50°C) is observed in zone A, whereas in

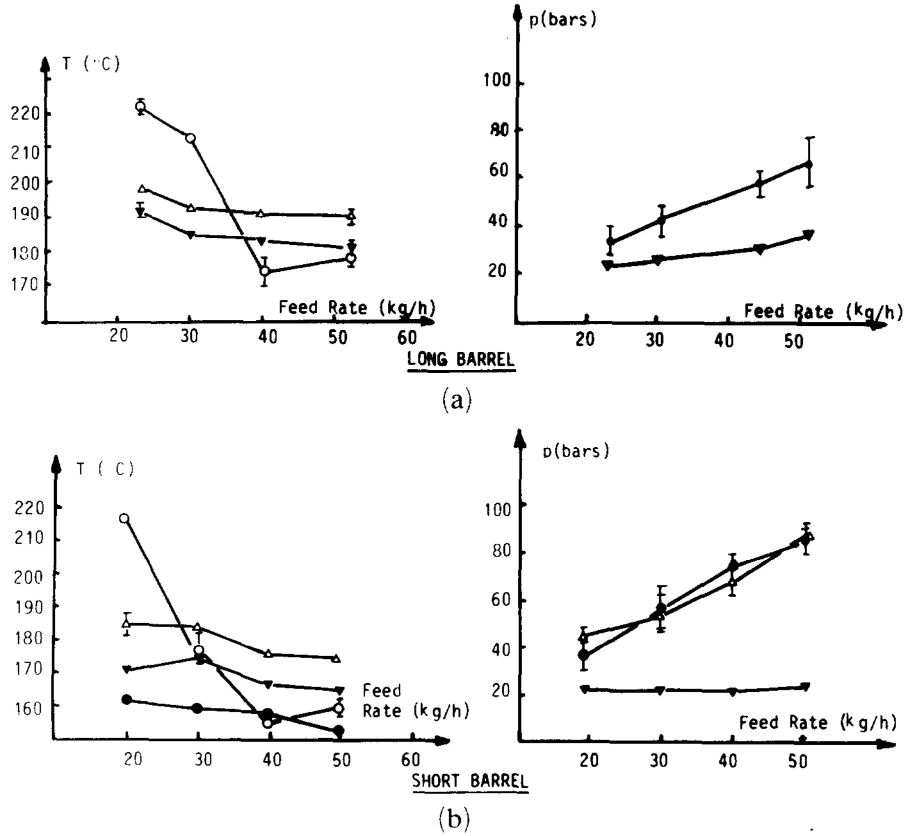


Fig. 10. Change in product pressure and temperature with feed rate at constant screw speed: (a) long barrel; (b) short barrel. (End of zone A: —o—; zone B: —▼—; zone C: —△—; zone D: —●—).

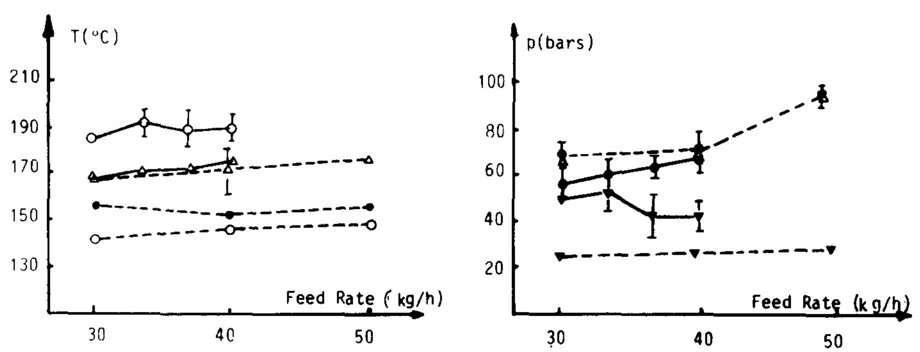


Fig. 11. Changes in product pressure and temperature with feed rate for two different degrees of fill ($Q/N = 17\%$: ——; $Q/N = 24\%$: - - - -). (End of zone A: —o—; zone B: —▼—; zone C: —△—; zone D: —●—).

zone C it stays at the same level (170°C) for both values of Q/N. The pressures in zones C and D remain the same (60 bar) for the two values of Q/N but rise (10–20 bar) when feed rate and screw speed are increased simultaneously. The pressure in zone B increases (20 bar) when Q/N decreases whereas it remains constant when feed rate and screw speed increase simultaneously.

(e) When the rate of water addition is increased from 5% to 30%, temperature and pressure decrease considerably (by 50°C and 40 bar) in every zone except zone B where the pressure remains constant (20 bar) (Fig. 12).

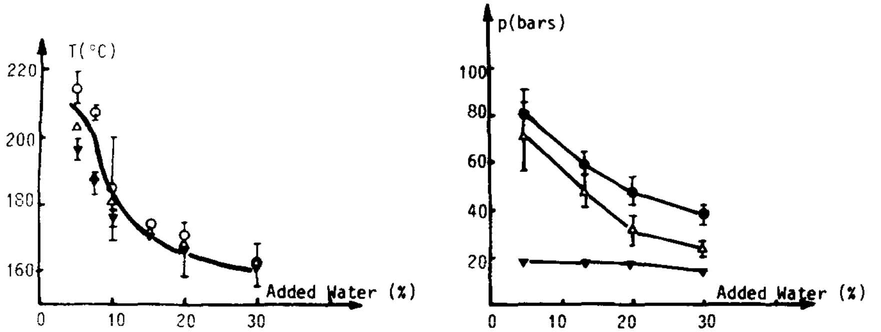


Fig. 12. Changes in product pressure and temperature with quantity of water added. (End of zone A: —o—; zone B: —▼—; zone C: —△—; zone D: —●—).

Discussion

The relationship between extrusion variables and the pressure and temperature of the product are summarized in Table 2. This table is obtained for specific experimental conditions and must not be interpreted as a general rule for twin-screw extruder working. However the temperature and pressure of the product at the die show the same trends as those observed by Mosso *et al.* (1982) (Table 3). The influence of added water is the same as observed by Senouci and Smith (1986) for potato starch extrusion cooking.

(a) Barrel temperature (Fig. 8). The results in zone A are not very significant because, as noted before, the temperature is not uniform in this zone. In other zones, the results merely show that an increase in the barrel temperature produces an increase of similar magnitude in product temperature, a consequence of thermal convection.

The viscosity of molten polymers generally increases as temperature decreases; this would explain why the pressure at the die rises when the temperature is reduced.

TABLE 2
Effect of Extrusion Variables on Temperature and Pressure of Product

Changed variable	*Range*	*Change in measurements*		
		Position of probes	*Temperature (°C)*	*Pressure (bar)*
		End of zone A	+50	0[a]
Temperature of the barrel at the die end (°C)	120–180	LDF: zone B	+50	0
		RSE: zone C	+40	—
		Die: zone D	+40	−20
		End of zone A	0	0
Screw speed (rpm)	130–250	LDF: zone B	—	−20
		RSE: zone C	+10	−20
		Die: zone D	0	−20
		End of zone A	−40	0
Feed rate (kg h^{-1})	20–50	LDF: zone B	−10	+10
		RSE: zone C	−10	+30
		Die: zone D	−10	+30
		End of zone A	−50	0
Added water (% wsb)	5–30	LDF: zone B	−50	0
		RSE: zone C	−50	−40
		Die: zone D	−50	−40

[a]0 signifies insignificant influence and — signifies influence not tested.

TABLE 3
Effect of Operating Variables on Temperature and Pressure of a Starch Based Mixture at the Die (from Mosso *et al.*, 1982)

Variable changed	*Range*	*Change in measurements*	
		Temperature (°C)	*Pressure (bar)*
Temperature of the barrel at the die end (°C)	150–190	+30	−10
Screw speed (rpm)	40–100	+5	−10
Feed rate (kg h^{-1})	25–50	−10	+40
Added water (% wsb)	10–30	−15	−30

(b) Screw speed (Fig. 9). The energy supplied by friction, as previously mentioned, is proportional to the velocity of the powder particles in zone A. At the same time, the quantity of heat transferred by convection from the barrel wall decreases as this velocity increases, since the residence time of the product at the hot barrel wall decreases. Thus, these two

physical phenomena, i.e. friction and convection, have opposite effects and that leads to a complex thermal behaviour in zone A. When the screw speed is increased, the energy due to shear in the reverse screw element, i.e. viscous dissipation, increases. Thus, temperature increases in zone C.

Molten starch exhibits non-Newtonian behaviour (Fletcher *et al.*, 1984; Vergnes *et al.*, 1985) and, as the shear increases with the screw speed, viscosity decreases and this may explain why pressure decreases in zone C and D.

(c) Feed rate (at constant screw speed) (Fig. 10). When the feed rate is increased at constant screw speed, the degree of fill of the screw channels increases in zone A. Heat production and flow due to friction and convection do not change, since they depend only on barrel temperature and screw speed, so each particle of starch is provided with less energy. This could explain the temperature drop in zone A when the feed rate increases. In zones B, C and D, the quantity of starch to be heated remains constant since the degree of fill is always 100%. So the temperature drop is much smaller in these zones.

The increase in pressure in zone D is explained by the flow of a molten polymer through a tube in which the pressure difference between input and output is related to the flow rate. The pressure drop across the RSE being slight as product flows through it, the same trend is observed for pressure in zone C. The length of the filled screw zone increases as the feed rate increases, so a smaller pressure gradient is necessary to balance the high pressure to be reached at the end of zone B, and therefore the pressure increase in zone B is smaller.

(d) Feed rate (at constant ratio Q/N (Fig. 11). The ratio Q/N is proportional to the degree of fill of the screw channels in zone A. If Q and N are changed simultaneously keeping Q/N constant, starch particles are provided with the same quantity of energy so the temperature in zone A remains constant. In zone C, starch completely fills the screw channel and screw speed and feed rate have slight and opposite effects (Fig. 9 and Fig. 10), so the degree of fill has little influence, and the temperature remains constant.

The pressure in zones C and D increases because feed rate has a greater influence than screw speed in the ranges explored (Fig. 9 and Fig. 10) and produces an effect similar to the increase of feed rate at constant screw speed.

(e) Water addition (Fig. 12). Since the viscosity of molten starch decreases as its water content increases (Fletcher *et al.*, 1984; Vergnes *et*

al., 1985), viscous dissipation is less which explains the temperature drop in zones C and D. Better knowledge of the influence of water on the thermal viscosity of starch would be needed to give a correct interpretation of the temperature drop in zone A.

The influence of water content on viscosity explains the pressure drop in zone C and D.

CONCLUSION

Despite the specificity of the material used in this study, some points seem well established:

- profiles of temperature and pressure show good agreement with the suggested division of the extruder into four functional zones. In the first, friction of starch particles on the surface of the barrel produces a significant increase in temperature; the role of each of the other sections depends on the position of the reverse screw element, in which temperature increases considerably at the high shear rate; the equilibrium point of the machine is set by the relationship between feed rate and pressure at the die.
- among the extrusion variables studied, the most influential is the added water; changes in the degree of fill (proportional to Q/N) combine the effects of screw speed and feed rate on temperature and pressure in all zones.

Some guidance for twin-screw extrusion-cooker operation can be drawn from these results. Further development of this work will include a theoretical study of the working conditions in the extruder; the qualitative physical interpretations and the data given here will be useful on which to base some hypotheses and to test the theoretical model.

ACKNOWLEDGEMENTS

The authors are grateful to E. Drouet and G. Lorand for extruder operation, also to J. P. Villemaire for making the temperature probes and to R. Cardenas for pressure signal processing.

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