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Numerical Simulation of the Extrusion Process for Food Materials in a Single-screw Extruder

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ABSTRACT

A numerical study of extrusion cooking of starch based materials in a single-screw extruder is carried out. The low moisture levels and high temperatures typically encountered in practical circumstances are considered. The starch conversion process is studied in the rheological region of the extruder which is often the last few turns of the screw, where the material is treated as a non-Newtonian fluid. A numerical method based on finite-difference approximation is employed to solve the governing non-linear equations for momentum, energy and mass conservation for a non-Newtonian fluid undergoing physicochemical changes. The initial conditions for the problem are taken from experimental observations. The screw configuration and the operating parameters, such as barrel temperature, screw speed and throughput, are varied to study their influence on the conversion of starch. It is found that 28% conversion is obtained due to viscous dissipation alone, whereas 61% conversion occurs by raising the barrel temperature by about 25°C above the inlet. It is also observed that, at any screw speed, a smaller flow rate caused by a smaller die diameter leads to a higher degree of conversion. Furthermore, it is found that the compression ratio of the screw has a significant influence on pressure rise, bulk temperature and average residence time. As the compression ratio increases the temperature increases but the residence time decreases. The former effect increases the degree of conversion where as the latter decreases the degree of conversion. Therefore there exists a compression ratio at which a minimum degree of conversion at the die is obtained. Copyright © 1996 Elsevier Science Limited

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NOMENCLATURE

A_m	Weight percentage of Amioca (dry solid)
A_w	Weight percentage of water in Amioca
B	Width of the screw channel
C	Moisture content in percentage (w.b.)
C_p	Specific heat at constant pressure
D_b	Barrel diameter
E_s	Shear activation energy
E_T	Thermal activation energy
H	Height of the screw channel at inlet
H_z	Height of screw channel at a given down-channel distance z
L	Total axial length of the screw channel
L_r	Total axial length of the rheological zone
K	Overall kinetic rate of reaction
K_m	Coefficient of moisture content in eqn (6)
K_T	Kinetic rate of reaction due to thermal effects
K_S	Kinetic rate of reaction due to shear effects
m	Order of the reaction
$\dot{m}$	Mass flow rate, or throughput (kg/s)
$\dot{M}$	Mass flow rate, or throughput (kg/h)
n	Power law index in eqn (6)
N	Screw speed (rpm)
P	Local pressure
R	Universal gas constant (cal/mole) in eqn (20)
S	Enthalpy change associated with gelatinization or conversion (W/m^3)
t	time (s)
T	Local temperature
u	Velocity in the x direction
V_a	Velocity in the direction of the screw axis
V_{bx}	Barrel velocity in the x direction
V_{bz}	Barrel velocity in the z direction
w	Velocity in the z direction
x	Cross-channel coordinate distance
X	Degree of conversion in percentage
y	Coordinate distance perpendicular to the screw and barrel surfaces
z	Coordinate distance in the down channel direction (along the screw helix)
z_{ir}	Down channel distance where the rheological zone begins

Greek letters

β	Compression ratio for tapered screw ($H/H_{z=z_{max}}$)
γ	Shear rate
κ	Thermal conductivity of the food material being extruded
μ	Viscosity
ρ	Density
τ	Average shear stress (dyne/cm^2) in eqn (21)
θ	Helix angle of the screw
ζ	Coordinate in the direction parallel to the screw axis

Subscripts

a	Axial
b	Barrel
dc	Down channel
dev	Developed

INTRODUCTION

Extrusion cooking is used for the manufacture of food products such as ready-to-eat breakfast cereals, expanded snacks, pasta, flat bread, soup and drink bases, etc. The process is reviewed by Harper (1981), Linko *et al.* (1981) and more recently by Mercier *et al.* (1989). Extrusion cooking process can be carried out in either a single-screw or a twin-screw extruder. In the present work, a single-screw extruder is considered because of its simpler geometry and more extensive use. A single-screw extruder cooker is basically a pump, a heat-exchanger and a bioreactor that simultaneously transports, mixes, heats, shears, stretches, shapes and transforms, chemically and physically, the material under elevated pressure and temperature in a short time. The raw material, in the form of a powder at ambient temperature, is fed into the hopper. The material first gets compacted and then softens and gelatinizes and/or melts to form a plasticized material (dough) which flows downstream in the extruder channel. Simultaneously, the material undergoes chemical and physical transformations due to thermal and shear effects. These constitute the process of cooking. Later the material is shaped by flow through the die at the end of the extruder. The extruded material undergoes further physical change as a result of extrudate expansion and moisture flash off upon exiting the die. The resulting porosity has a major influence on the product properties which reflect the effects of the extrusion cooking process.

The process of extrusion cooking is not well understood because it involves both chemical and physical changes in the material and due to interdependence of product properties and quality. The chemical changes determine the extent of molecular modification such as starch gelatinization and dextrinization. The physical changes affect the textural properties such as hardness, elasticity and chewiness, as well as other sensory attributes like color and flavor which are the primary factors in how a product is received by the consumer. In the present work, particular attention is focused on the quantification of the physiochemical transformations (conversion) of starchy materials that occur during the extrusion process in a single-screw extruder. The conversion process involves both gelatinization and melting of starch granules because of the low moisture level ($\leq 40\%$). The mechanism of starch melting is similar to that of thermo-plastics (polymers). However, the gelatinization process is more complex because of the interaction of water with starch. Gelatinization takes place at relatively lower temperatures as compared to the melting process. It involves three steps which include the swelling of starch granules as the added water disrupts the granule crystallinity, the diffusion of amylose out of the starch granules as more water and heat are added and, finally, the gel formation as the starch granules collapse (Donovan, 1979; Wang *et al.*, 1991).

The extrusion of plastics was a well developed process by the beginning of the 1940s. Many studies have considered the development of mathematical models to understand the flow of polymers by using different numerical and analytical techniques (Tadmor & Klein, 1978; Tadmor & Gogos, 1979; Fenner, 1980; Rauwendaal, 1986; Janssen, 1988; Karwe & Jaluria, 1990; Gopalakrishna *et al.*, 1992). These models are very successful for plastics because the physical and rheological properties of plastic materials are well characterized. On the other hand, the modeling of food extrusion began in the last 20 years, as reviewed by Baird and Reed (1989). The main difficulties in modeling food processes are due to the complexity of the raw materials and the property changes which are due to both physical and chemical effects. During extrusion of food materials the heterogeneous nature of the material, the phase transitions, the denaturation of protein and other ingredients and the strong dependence of the properties on the moisture level and on temperature, complicate the determination of the physical and rheological properties of the food material undergoing thermal processing. This makes the mathematical modeling a much more difficult task than the corresponding problem for plastics.

The objective of the present work is to study the behavior of starch based materials under the high shear and temperature environment in an extruder. A numerical simulation of flow of a starchy material inside a single-screw extruder is carried out. Corn starch with 97% amylopectin known as Amioca was considered in the present study. Numerical simulation is carried out at low moisture levels (15–40%) and high temperatures (80–180°C). During the extrusion process, the thermal energy may be transferred from and to the barrel. Heat is also generated by viscous dissipation. Since thermal effects are very important in the starch conversion process an effort is made to compare two cases: one in which heat transfer is supplied by the hot barrel and in the other the barrel is maintained at the same temperature as the inlet. Thus the temperature rise in the second case is largely due to viscous dissipation. The effect of shear on the conversion is thus examined.

The rheological properties of the starch material are taken as functions of temperature, shear rate and moisture level. As the material moves along the extruder the temperature of the material changes because of the heat supplied from the barrel and also due to viscous dissipation. When the barrel is maintained at the inlet temperature, the conversion of starch occurs due to viscous dissipation alone.

The screw geometry is another important parameter in the problem. In the current work, the effects of taper of the screw channel is considered since it can influence the shear environment, residence time distribution and the mixing of starch material. Different compression ratios of a typical practical extruder are considered and the extruder response is studied. The opposing effects of the two important parameters namely, temperature and residence time, on the degree of conversion is studied by varying the compression ratio. It is found that there exists a compression ratio at which the degree of conversion is minimum.

MATHEMATICAL FORMULATION

The food material in a single screw extruder is transported due to the drag at the barrel surface and the presence of the screw flights, which make the fluid move towards the die. The flow configuration can be considerably simplified by treating the screw as stationary and rotating the barrel in the opposite direction to that of the screw (Tadmor & Klein, 1978). Also, if the height of the screw channel is much less than the barrel diameter, as is the case for many practical extruders, the screw channel can be mathematically modeled as unwrapped. The coordinate system can be fixed to the screw for convenience. The barrel is moved at an angle θ to the central vertical plane of the channel. For further details on this modeling, see Fenner (1977), Karwe and Jaluria (1990), among others. The schematic of a single-screw extruder is shown in Fig. 1(a) and the unwrapped screw channel is shown in Fig. 1(b).

Since the viscosity of most of the starch based materials is very high, leading to Reynolds numbers much less than unity, the inertia terms in the Navier–Stokes equation can be neglected. However, the Prandtl number is quite large making it essential to retain the convection terms in the energy equation. The flow in the unwrapped screw channel is treated as a flow in a duct of width B and height H, as

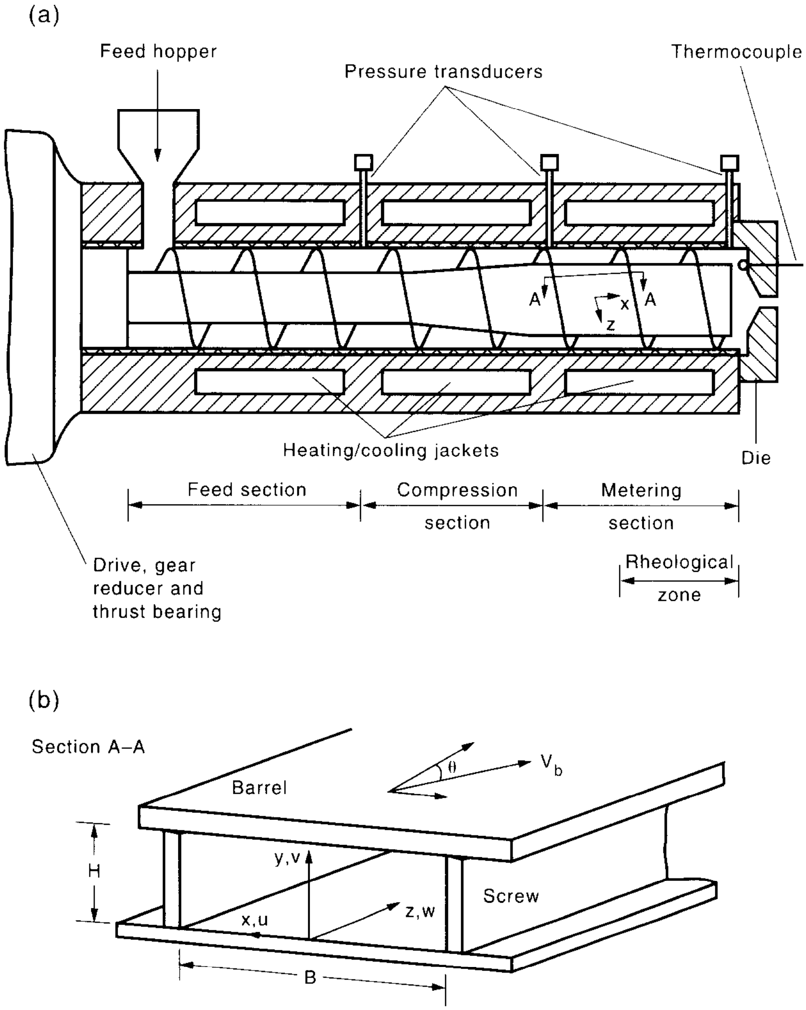

Fig. 1. Screw channel geometry for a single-screw extruder.

shown in Fig. 1(b). For a shallow screw channel, $H \ll B$ and for typically wide channels the effect of screw flights can be neglected (Pearson, 1967). Thus, the Y-momentum equation does not appear in the governing equations. The diffusion of momentum in the down channel direction, z, is often negligible compared to that in the y direction, because of the much smaller distances in the y direction. Then, the governing equations can be written as (Schlichting, 1979),
x-momentum equation:

$$\frac{\partial P}{\partial x} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \tag{1}$$

z-momentum equation:

$$\frac{\partial P}{\partial z} = \frac{\partial}{\partial y}\left(\mu \frac{\partial w}{\partial y}\right) \tag{2}$$

Continuity:

$$\int_0^H \rho u dy = 0 \tag{3}$$

$$\int_0^H \rho B w dy = \dot{m} \tag{4}$$

In conservation of energy, the effects of viscous dissipation and heat transfer with the barrel, convection in the down channel direction are retained. However, the diffusion of energy in the down channel direction is usually small compared to convection in that direction (Karwe & Jaluria, 1990). This effect has also been studied in detail by Chiruvella *et al.* (1995). Therefore the energy equation can be written as,

Energy equation:

$$\frac{\partial}{\partial z}(\rho C_p w T) = \frac{\partial}{\partial y}\left(\kappa \frac{\partial T}{\partial y}\right) + \mu\left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right] + S \tag{5}$$

where S is the energy absorbed or released due to gelatinization or conversion. In the present study this quantity is neglected as a first approximation, since the value of S has been found to be small for the materials of interest (Lund, 1983).

It is very complex to measure the rheological properties of food dough because of the time-dependent changes in the material properties, the reactive nature of food ingredients and the wide range of temperature, pressure and moisture content that have to be considered in such measurements. Over the years, researchers have developed various empirical viscosity models for cereal dough (Harper, 1978), with the assumptions that the apparent viscosity μ has an Arrhenius dependence on temperature T, an exponential dependence on moisture content C and a power-law dependence on shear rate $\dot{\gamma}$. Thus, the rheological equation can then be written as,

$$\mu = \mu_0 \dot{\gamma}^{n-1} \exp\left(\frac{\Delta E}{RT}\right) \exp(-K_m C) \tag{6}$$

where μ_o and K_m are constants, n is the power-law index of the pseudoplastic material, ΔE is the activation energy and R is universal gas constant. Here $\dot{\gamma}$ is the shear rate given as,

$$\dot{\gamma} = \left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right]^{\frac{1}{2}}. \tag{7}$$

Lai and Kokini (1990) and Chang (1992) used Harper's rheological model [eqn (6)] to predict the viscosity of waxy corn starch in extrusion process. They obtained the following equation from their detailed measurement:

$$\mu = 0{\cdot}44\dot{\gamma}^{-0{\cdot}682}\exp\left(\frac{5109}{T}\right)\exp(-0{\cdot}148C) \tag{7}$$

when $T < 110°C$ and

$$\mu = \exp\left(-0{\cdot}865C + 12\frac{12543}{T} - 0{\cdot}608\ln(\dot{\gamma}) - 8{\cdot}279\frac{C}{T} + 0{\cdot}0018CT - 17{\cdot}667\right) \tag{8}$$

when $T \geq 110°C$.

Assuming that the total moisture content does not change during the extrusion process, the species conservation equation for moisture and starch system (Wang *et al.*, 1989) is given as,

$$\frac{d}{dt}(1-X) = -K(1-X)^m \tag{9}$$

where X is the degree of conversion, defined as,

$$X = \frac{M_0 - M_t}{M_0 - M_f}. \tag{10}$$

Here M_0 is the initial amount of unconverted starch, M_f is the final amount of unconverted starch and M_t is the amount of unconverted starch at time t. The order of the reaction is m and K is the reaction rate.

For a tapered screw channel, with a compression ratio $\beta = H/H_{z=z_{max}}$, the channel height at any down channel location can be expressed as,

$$H_z = \left[1 - \frac{z}{L_{dc}}\left(1 - \frac{1}{\beta}\right)\right]H \tag{11}$$

Defining $y^* = H\ (y/H_z)$ and expressing the governing equations in terms of y^* and dropping the asterisk sign for convenience one obtains,
x-momentum equation:

$$\frac{\partial P}{\partial x} = \left(\frac{H}{H_z}\right)^2 \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \tag{12}$$

z-momentum equation:

$$\frac{\partial P}{\partial z}=\left(\frac{H}{H_z}\right)^2\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right) \tag{13}$$

Continuity:

$$\int_0^H \rho u \mathrm{d}y=0 \tag{14}$$

$$\left(\frac{H}{H_z}\right)\int_0^H \rho B w \mathrm{d}y=\dot{m} \tag{15}$$

Energy equation:

$$\frac{\partial}{\partial z}(\rho C_p wT)=\left(\frac{H}{H_z}\right)^2\frac{\partial}{\partial y}\left(\kappa\frac{\partial T}{\partial y}\right)+\left(\frac{H}{H_z}\right)^2\mu\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right] \tag{16}$$

A zero order reaction is a good approximation for the phase transition and chemical transformation in starch materials, see Bhattacharya (1987) and Wang *et al.* (1989). The differential increment in time t can be defined as $\Delta t=\Delta\zeta/V_a$ where ζ is the axial coordinate and V_a is the axial velocity component. Then eqn (9) can be represented along the axial direction as,

$$V_a\frac{\mathrm{d}X}{\mathrm{d}\zeta}=K \tag{17}$$

where,

$$V_a=w\sin\theta+u\cos\theta \quad \zeta=z/\sin\theta \tag{17}$$

The boundary conditions are given as,

$$u(y=0)=0 \ \ u(y=H)=-V_{bx}$$

$$w(y=0)=0 \ \ w(y=H)=V_{bz}$$

$$\frac{\partial T}{\partial y}(y=0)=0 \ \ T(y=H)=T_b$$

$$u(z=z_{ir})=u_{dev} w(z=z_{ir})=w_{dev}$$

$$T(z=z_{ir})=T_{ir} \ \ X(z=z_{ir})=0{\cdot}0 \tag{18}$$

where,

$$V_{bx}=\frac{\pi D_b N\ \sin\ \theta}{60};V_{bz}=\frac{\pi D_b N\ \cos\ \theta}{60}$$

and u_{dev} and w_{dev} are the velocities calculated using the momentum and continuity equations at the inlet temperature T_{ir},

The reaction rate K for amioca is given by Wang *et al.* (1989) as,

TABLE 1
Thermal Activation Energies and Coefficients for Waxy Corn Amioca Starch with Different Moisture Contents by DSC Treatment. The Data is Taken from Zheng (1993)

Material : Amioca *70°C ≤ T ≤ 170°C* *Moisture %*	E_T *[kcal/mole]*	K_{T0} *[min^{-1}]*
20	26·96	$1{\cdot}509 \times 10^{13}$
25	53·43	$8{\cdot}003 \times 10^{26}$
30	44·25	$2{\cdot}590 \times 10^{25}$
35	16·13	$2{\cdot}177 \times 10^{8}$

$$K = K_T + K_S \tag{19}$$

where

$$K_T = K_{T0}e^{-E_T/(RT)} \tag{20}$$

$$K_S = K_{S0}e^{-E_S/(\tau^\nu)} \tag{21}$$

and ν is given as,

$$\nu = \frac{16\,200}{(1{\cdot}55A_m + A_w)}. \tag{22}$$

The values of these constants, for amioca, at the given operating temperatures are listed in Tables 1 and 2. The shear activation energy E_s is correlated (Zheng, 1993) as a function of temperature at different moisture levels as,

$$E_s = 2{\cdot}86 \times 10^9 \exp(-0{\cdot}058T) \quad C = 35\%$$

$$E_s = 5{\cdot}56 \times 10^8 \exp(-0{\cdot}052T) \quad C = 30\%. \tag{23}$$

The physical properties of Amioca which are used for the numerical calculations are given in Table 3. The governing equations described above were solved numerically as described in the following section.

TABLE 2
Shear Activation Energies and Coefficients for Waxy Corn Amioca Starch with Different Moisture Content. The Data is Taken from Zheng (1993)

Material: Amioca	*30% Moisture (w.b.)*		*35% Moisture (w.b.)*	
Temp °C	E_S *[cal/mole]*	K_{S0} *[min^{-1}]*	E_S *[cal/mole]*	K_{T0} *[min^{-1}]*
70	—	—	2·69	20·96
80	4·59	64·26	1·97	27·22
90	3·31	88·68	1·22	20·86
100	1·92	43·38	—	—

TABLE 3
Physical Properties of Amioca

ρ [kg/m^3]	C_p *[J/kgK]*	κ [W/M K]
1200	2060	0·17

NUMERICAL SCHEME

The governing momentum and energy equations are discretized using the control volume finite difference method (Chiruvella *et al.*, 1995). The velocity and pressure are coupled with each other through the integral form of the continuity equation. The viscosity of the non-Newtonian food material is a function of both temperature and shear rate, which is a function of the velocities. Therefore the energy and momentum equations are coupled through the viscosity.

Since the velocity distribution and the temperature at the inlet to the computational domain are taken to be known, the temperature field in the next down channel location can be calculated by marching using the energy eqn (16). The tridiagonal matrix algorithm (TDMA) (Patankar, 1980) is used to obtain the temperature distribution which satisfies the boundary conditions specified in eqn (18). Since the energy and momentum equations are coupled to each other, at each down channel location the momentum and energy eqns (12), (13) and (16), are solved iteratively, as discussed below, till the continuity eqns (14) and (15) are satisfied.

1. Using the temperature and velocity values at $z = 0$, march to the new down channel location ($z = \Delta z$) by using the energy equation.
2. Solve the energy equation.
3. Solve z-momentum equation.
4. Solve x-momentum equation.
5. Check the continuity eqns (14) and (15).
6. If eqns (14) and (15) are satisfied to a relative error criterion of 0·001% then goto step 8, otherwise goto step 7.
7. Calculate the viscosity from eqn (6) and go to step 2.
8. Increment the down channel location by Δz and goto step 2.

The details of the iterative scheme, involving updating of the viscosity, pressure, velocity and temperature, are discussed in detail by Chiruvella *et al.* (1995). The numerical program was tested for grid dependency and was found to be grid independent. Once the temperature and the velocities are known at every down channel location, eqn (17) is solved to determine the degree of conversion.

RESULTS AND DISCUSSION

During food extrusion, the material behaves like a rheological non-Newtonian fluid in the last few turns of the screw, near the die. The length of the rheological zone is not known apriori. Therefore numerical predictions were made by varying the length of the rheological zone until the predicted degree of conversion matched with experimentally determined degree of conversion. The experimental results of Lai and Kokini (1990) on a Brabender single screw extruder were used in the study. The

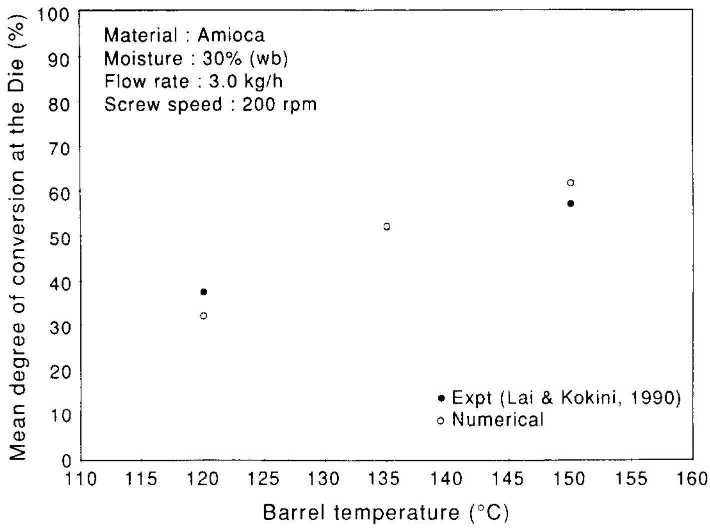

Fig. 2. Comparison between the experiments and numerical predictions.

same rheological length was used to predict the degree of conversion for the other experiments keeping the screw speed and mass flow rate unchanged. Figure 2 shows the comparison obtained between the numerical predictions and the experimental results. The experiments were performed at three different barrel temperatures. The experiment performed at 135°C was used to determine the length of the rheological zone which was found to be 4·325% of the total axial length of the extruder.

Viscous dissipation plays an important role in the extrusion of food materials by means of a single screw extruder. The effect of viscous dissipation in a single screw extruder can be investigated by maintaining the barrel at the same temperature as the inlet. The screw is treated as adiabatic here, this being a fairly good approximation, as shown by Sastrohartono *et al.* (1995). In the case described here, the inlet and barrel temperatures are kept at 90°C. In the case of a full screw and for a selected die, a particular flow rate arises for a certain screw speed. In which case, at a constant screw speed, the flow rate can be changed only by changing the size of the die.

Figures 3, 4 and 5 show the numerically obtained screw characteristic curves during extrusion of Amioca with 30% moisture (w.b.) on a Brabender single screw extruder. Figure 3 shows the screw characteristics in terms of the variation of bulk temperature at the die with the mass flow rate, at different screw speeds. Since the barrel and the fluid inlet are maintained at a temperature of 90°C, the temperature of the material rises only as a result of viscous dissipation. The heat generated due to viscous dissipation will be partially conducted through the barrel walls, the remaining being convected by the fluid. As the flow rate increases, the average residence time* of the fluid decreases. Therefore the amount of energy transferred

*The average residence time of the fluid is defined as the ratio of the total volume of the filled screw channel to the volume flow rate.

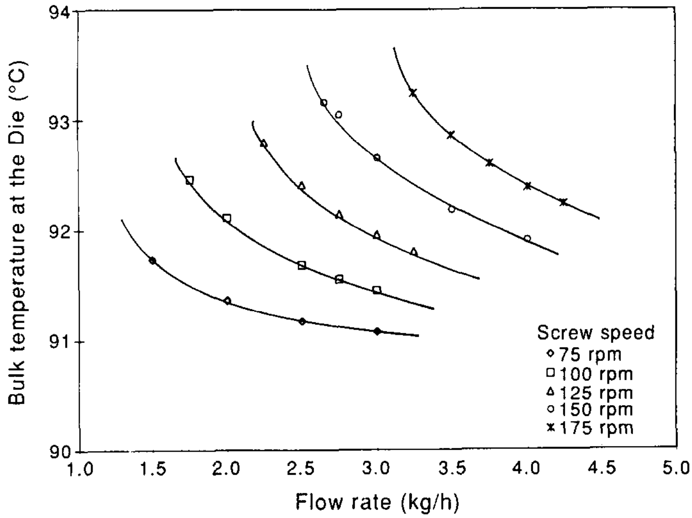

Fig. 3. Predicted variation of bulk temperature at the die with the flow rate at different screw speeds.

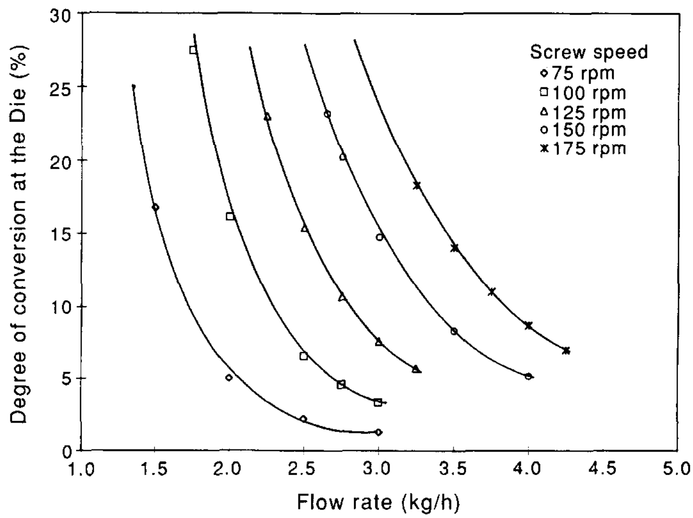

Fig. 4. Predicted variation of mean degree of conversion at the die with the flow rate at different screw speeds.

to the fluid by conduction through the barrel walls reduces with an increase in the flow rate. As a result, the bulk temperature at the die decreases with the flow rate (Chiruvella *et al.*, 1995). Also, at a constant flow rate, the shear rate and the viscous dissipation which are functions of velocity gradients will increase with increase in screw speed. Hence, the amount of heat generated and the bulk temperature at the die increase with increase in screw speed.

The variation of the mean degree of conversion at the die with the flow rate is shown in Fig. 4. Since the residence time decreases with an increase in the flow rate, the time available for the conversion reaction to take place also decreases. Therefore, at a constant screw speed the degree of conversion at the die decreases with an increase in flow rate.

It was discussed before that at a constant flow rate an increase in screw speed results in an increase in shear rate and temperature which favor an increase in degree of conversion. The reaction rate constant increases with both temperature and the shear rate. Hence, at a constant flow rate, the degree of conversion at the die increases with screw speed.

The viscosity of the rheological fluid depends upon the degree of conversion. If the variation of viscosity with the degree of conversion is known then the reaction kinetics equation has to be coupled with the energy and momentum equations. Due to lack of information on variation of viscosity with conversion, the equation for conversion is solved after the velocity and temperature fields are determined.

The variation of pressure at the die with the mass flow rate at different screw speeds is shown in Fig. 5. For a given screw speed, an increase in the mass flow rate can be achieved only by making the die opening larger, assuming that all of the screw channel is full. A die with larger opening need smaller pressure rise at the end of the screw.

The effect of the barrel temperature on the degree of conversion is discussed

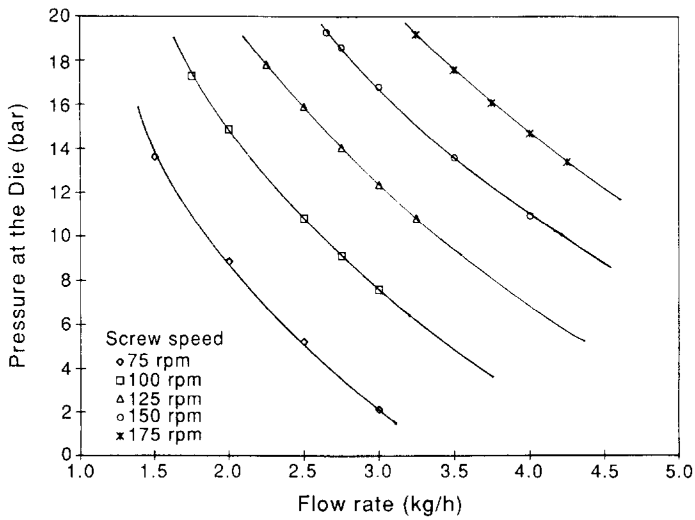

Fig. 5. Predicted variation of pressure at the die with the flow rate at different screw speeds.

next. Figures 6 and 7 show the isotherms and the conversion contours in the rheological zone of a 0·75″ diameter single screw extruder having $L/D = 20$ and manufactured by Brabender. To show the effect of barrel heating and viscous dissipation on the degree of conversion, the barrel temperature is varied from 90 to 115°C. The following conditions are used in the simulation: mass flow rate = 10 kg/h, screw speed = 100 rpm, compression ratio = 3·0 and length of rheological zone as 4·325% of the total length. When the barrel and the inlet temperatures are the same, the heating in the screw channel is largely caused by the viscous dissipation. A higher degree of conversion is seen at the screw root and at the barrel because of the longer residence time of flow particles near the solid walls. When the barrel temperature is changed from 90 to 115°C, the degree of conversion of the material is considerably higher because of barrel heating and as well as viscous dissipation. When the barrel is maintained at 90°C, it can be seen from the isotherm plot that the entire length of the barrel in the rheological zone has to be cooled to maintain the barrel at 90°C, whereas, it has to be heated to a certain length and then cooled in the case where the barrel is maintained at 115°C.

The effect of the compression ratio on the bulk temperature, mean degree of conversion and pressure is now discussed. In order to show the trends in the

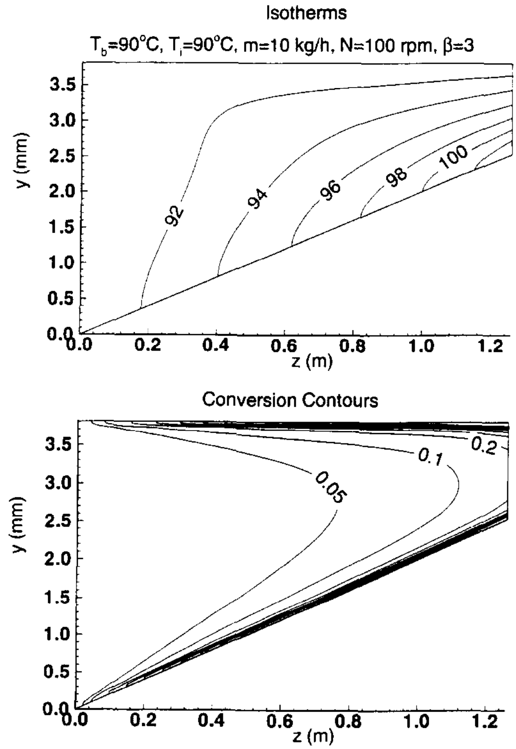

Fig. 6. Isotherms and conversion contours while extruding amioca in a practical screw extruder made by Brabender, when the inlet and barrel temperatures are maintained as equal.

pressure development along the screw channel, the entire length of the screw is treated as the rheological region. The barrel and the inlet temperatures are maintained at 90°C and Amioca with 30% moisture is extruded at 10·0 kg/h using the Brabender screw extruder at a screw speed of 100 rpm. Figure 8 shows the variation of the bulk temperature with the down channel distance at different compression ratios. As the compression ratio increases, the channel depth decreases, thereby increasing the shear rate and also the viscous dissipation. As the compression ratio increases, the volume of the screw channel decreases. Therefore, at a constant flow rate, the average residence time of the material decreases with the increase in the compression ratio. Therefore, the fluid loses less heat through the barrel because of the lower residence time (contact time) and, hence, higher bulk temperatures are seen at higher compression ratios.

The variation of the mean degree of conversion with the down channel distance is seen in Fig. 9. The mean degree of conversion depends on temperature and the residence time. Higher residence times and higher temperatures favor a higher degree of conversion. As seen in Fig. 8 the temperature increases with compression ratio, but the residence time decreases as the throughput is maintained constant. The opposing effects of the increase in temperature and the decrease in residence time on the degree of conversion are seen in Fig. 9 as a function of compression

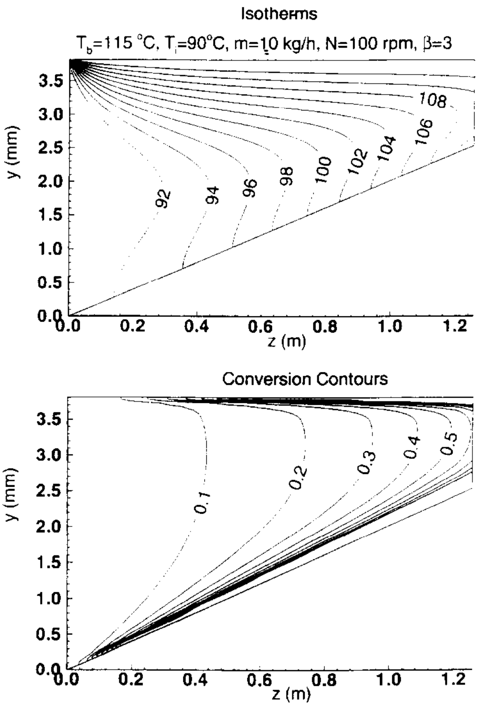

Fig. 7. Isotherms and conversion contours while extruding amioca in a practical screw extruder, when the inlet and barrel temperatures are different.

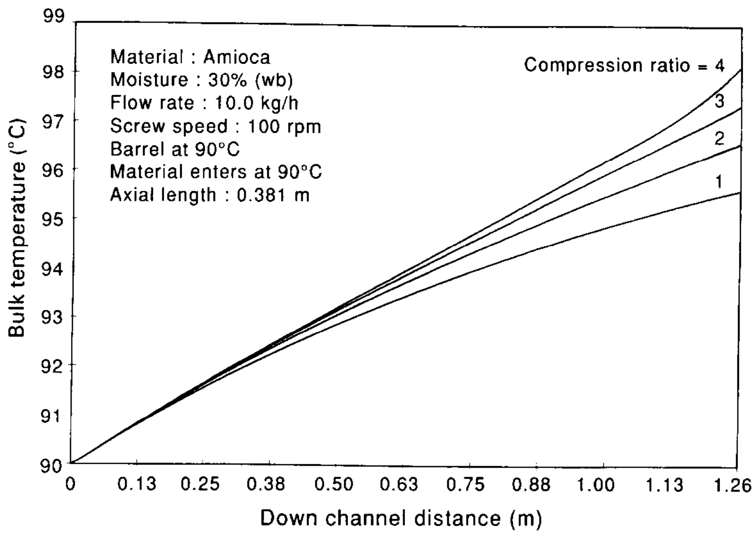

Fig. 8. Predicted variation of bulk temperature with the down channel distance while extruding amioca with different compression ratios.

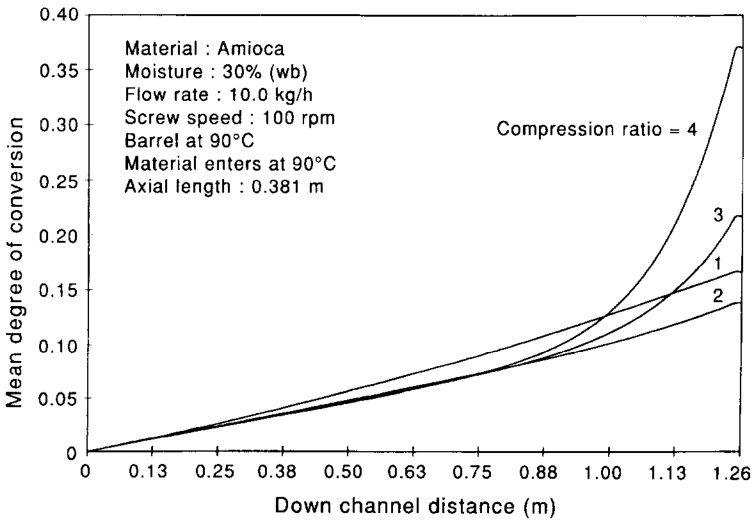

Fig. 9. Predicted variation of mean degree of conversion with the down channel distance while extruding amioca with different compression ratios.

ratio. At given flow rate and screw speed, the screw without taper results in a mean degree of conversion which is directly proportional to the length of the screw. Where as the screw with compression ratio greater than one yields the degree of conversion proportional to the down channel length to certain length of the screw channel but yield very different results afterwards. For the length and operating conditions considered in the present study, the screw with a compression ratio of 2 yields the lowest mean degree of conversion at the die. At a compression ratio of 1 the residence time is longer as compared to that at a compression ratio of 4. At the compression ratio of 1 the residence time plays a role in obtaining higher conversion, where as at compression ratio of 4 the viscous dissipation or shear is the major contributor in obtaining higher degree of conversion. Therefore in between these compression ratios there occurs a situation where the residence time or the temperature are high enough to obtain the minimum degree of conversion. A similar situation occurred at compression ratio of 2 for the above selected operating conditions.

The variation of pressure with the down channel distance is shown in Fig. 10 at different compression ratios. The flow rate and the screw speed are maintained the same in all the cases. As the compression ratio increases, the available volume for the fluid flow decreases. Therefore, the velocity profile at the entrance, which looks like the one in the drag flow, modifies along the down channel to that in the pressure flow situation. As a result in a tapered screw, the pressure increases and then decreases. Negative pressures are not possible in a practical situation. The results in Fig. 10 show that to convey the same amount of material through non-tapered and tapered screws at the same screw speed, the material should enter the tapered screw at a high pressure. However, the material usually enters the screw channel at the inlet (hopper) at atmospheric pressure and hence the conditions that

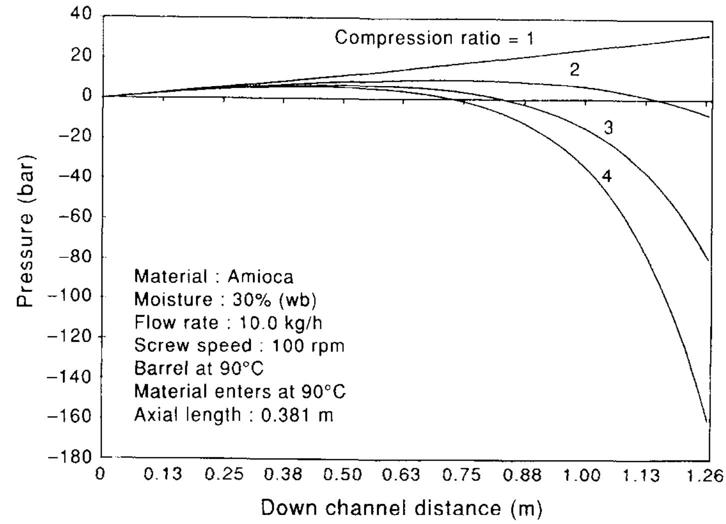

Fig. 10. Predicted variation of pressure with the down channel distance while extruding amioca with different compression ratios.

result in die pressures lower than the atmospheric pressure are of little practical interests. The advantage of using the numerical model is that these situations can be predicted *a priori* and can be ruled out as impractical.

CONCLUSIONS

Extrusion cooking of a starchy material Amioca, at low moisture levels and high temperatures is modeled using a finite difference numerical model. The conversion process is studied in the rheological region of the extruder. The effect of viscous dissipation on the conversion is studied at two different barrel temperatures. Two fold increase in conversion of the material occurs by raising the barrel temperature by about 25°C above the inlet temperature, whereas only 28% conversion occurs when the barrel is at the same temperature as the inlet. At a given screw speed, higher levels of conversion are obtained at lower flow rates. This implies that at a given screw speed, the narrowest die yields the highest level of conversion. At a fixed flow rate and screw speed, as the compression ratio is increased the bulk temperature increases with the down channel distance while the average residence time decreases. Minimum mean degree of conversion at the die is found to occur at a compression ratio of 2, when the compression ratio varies between 1 and 4.

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