Food Engineering Progress
Vol. 7, No. 2. pp. 80~87 (2002.5)

Effects of Extrusion Conditions on Pasting Properties of Potato and Potato-Wheat Flour Mixture

Jae Yoon Cha, Yong-Jin Cho, Chong-Tai Kim, Chul-Jin Kim and P.K.W. Ng*

Korea Food Research Institute
**Department of Food Science and Human Nutrition, Michigan State University*

Abstract

The purpose of this study was to develop extrusion process of fresh potato and to study the effects of extrusion condition on the pasting properties of extruded potato products. The blend of pressed potato and wheat flour and pressed potatoes were extruded at different die exit temperatures (110-160°C) and screw speed of 100 rpm using a twin-screw extruder with conveying, high and low shear screw configuration. The viscosity-related parameters, such as peak viscosity, through, final viscosity, peak time, and pasting temperature of the feed materials and extruded products, were studied using a rapid visco analyzer (RVA). Their water solubility index (WSI) and water absorption index (WAI) were also studied. The peak viscosity, through, final viscosity, and peak time of pressed potato extrudates and potato-wheat flour mixture extrudates decreased as die exit temperature increased. The WSI and WAI of potato products increased as die exit temperature increased. When high shear screw configuration was used, the values of viscosity-related parameters were lower than those when low shear screw configuration was used. The potato-wheat flour mixture products obtained different degrees of depolymerization from fresh potatoes and wheat flour depending on die exit temperature and screw configuration.

Key words: Extrusion, potato, wheat flour, pasting property, rapid visco analyzer

Introduction

Many food manufacturers for continuous production of snack foods, breakfast cereals, and crispbreads have adopted the extrusion process. The introduction of the twin-screw extruder has widened the scope of food extrusion in the manufacture of cereals and starches, ready-to-eat cereals, infant formulas, snack foods, soft moist pet foods, breadings, and coatings. Extrusion-processed potato snacks have captured large segments of the market share once dominated by potato chips. Dehydrated potato granules or flakes and other ingredients are mixed with water and then fed through an extruder to produce potato snacks. The effects of extrusion have been studied on potato starch (Mercier, 1977; Della Valle *et al.*, 1995), potato flakes (Maga and Cohen, 1978), and blends of potato and wheat flours (Bhattacharya *et al.*, 1999).

The thermal and mechanical energies used during extrusion change the physical and rheological properties of the raw food materials as well as the functional properties of the extruded food products (Davidson, 1992). The rheological properties include the paste consistency and viscosity-related parameters that are used to characterize quality attributes of the extruded food products. Pasting properties of extrudates are important when the pregelatinized extrudate powders are used as food thickeners. Changes in viscosity of extrudate powders produced under various operating conditions have been studied to determine the factors affecting pasting properties (Anderson *et al.*, 1969; Lawton *et al.*, 1972; Owusu-Ansan *et al.*, 1983; Mason and Hoseney, 1986; Ryu *et al.*, 1993; Bhattacharya *et al.*, 1999). Walker *et al.* (1988) reported first the use of a modified rapid visco analyzer (RVA) to study the pasting characteristics of starch gelatinization, disintegration, swelling, and gelling ability. The advantages of the RVA technique over the commonly

Corresponding author: Jae Yoon Cha, Biosystems Engineering Team, Korea Food Research Institute, San 46-1, Baekhyun-Dong, Bundang-Ku, Songnam-Si, Kyonggi-Do 463-746, Republic of Korea.
Phone: 031-780-9139, E-mail: jycha64@hanmail.net

used viscograph system are the requirements for only a small sample, easy operation, and high sensitivity in distinguishing among samples.

The use of dehydrated potato granules for the manufacture of snacks invariably involves the addition of water that was removed during the dehydration process. In the studies referring to potato starch extrusion, processing difficulties have been reported that were solved by running the process at higher moisture content and shorter screw length (Mercier, 1977; Della Valle *et al.*, 1995). Ferdinand *et al.* (1989) studied the extrusion cooking of fresh potatoes as an alternative to the use of the dehydrated granules. The energy consumption was reduced during extrusion when fresh potato was used instead of dehydrated potato. However, the effect of extrusion conditions on the properties of fresh potato products has not been reported. The utilization of fresh potatoes for extrusion may reduce the detrimental effects that occur when tubers that are unsuitable for stock reach the fresh market.

In the present study, three differently pre-processed potatoes were extruded at varying die exit temperatures and screw configuration. The specific objectives of this study were (1) to develop the processes for extrusion dehydration and carbohydrate modification of fresh potato, (2) to study the effects of die exit temperature and screw configuration on the pasting properties (RVA profile, WSI, and WAI), and (3) to develop an empirical model to predict peak viscosity and final viscosity of extruded potato products.

Materials and Methods

Materials

Potatoes were grown at the Michigan State University Montcalm Research farm, East Lansing, Michigan. Raw potatoes were cleaned and peeled by using a peeling knife and then cut into cubes (about 2 cm^3). The cubes were then ground using a food processor. The ground potatoes were pressed to reduce their moisture content from 85% to 73% (w.b.). The pressed potatoes were mixed with soft wheat flour (12% M.C.), which was obtained from the King Milling Co. (Lowell, MI), at mixing ratio of 50% using a dough mixer (model N50, Hobart, Ontario, Canada) with a wire.

Proximate composition

The pressed potato and the mixture of potato with wheat flour were dried at 40°C overnight using a forced-air oven and ground into powder using a cyclone sample mill (Udy Corporation, Fort Collins, CO) equipped with a 0.5 mm mesh screen as a control. Moisture, nitrogen, starch, and ash contents of the ground samples and wheat flour were determined by AACC methods 44-19, 46-13, 76-13, and 08-03, respectively (AACC, 2000). Fiber content was determined by AOAC method 991.43 (AOAC, 1995). Protein content was estimated using the N conversion factor of 6.25. Fat content was obtained by subtraction of the other contents from 100%. All samples were run in duplicate.

Experimental design

A split-plot design was used to evaluate the effects of extrusion temperature and amount of shear on the physical properties of extruded potato products. Whole plot was screw configuration (low shear and high shear), and sub plot was die exit temperatures (110, 135, and 160°C). Response variables were viscosity properties, water solubility index, and water absorption index. The Statistical Analysis System (SAS Institute, Cary, NC) was used for all statistical analyses. Means were compared by the least significant difference (LSD) test at the $\alpha = 0.05$ level.

Extrusion process

The pressed potato and potato-wheat flour mixture samples were extruded at different barrel temperatures using a co-rotating and intermeshing twin-screw extruder (model MPF-19, APV Baker, Grand Rapids, MI), with a 19-mm barrel diameter and 25:1 length to diameter ratio. The die used for this study had a single circular orifice with a 3-mm diameter opening. The barrel temperature of each zone, from feed end (zone 1) to melt end (zone 4) of the extruder and the temperature at the die exit are listed in Table 1. Three screw configurations, such as conveying shear (CS), low shear (LS) and high shear (HS) are listed in Table 2. The conveying shear screw configuration was used for pressed potatoes extrusion, and high and low shear screw configurations were used for the potato-wheat flour mixture extrusion. The feed rate of feed materials was dependent on screw speed, which was set at 100 rpm. The potato-wheat flour mixture samples were each extruded in duplicate for each die exit temperature studied. After extrusion, extrudates were dried at 40°C overnight using a forced-air oven. The dried samples (~12% M.C. (w.b.)) were first ground into small particles using a micro-mill (Bel-Art products, Pequannock, NJ), and then further ground into powder using a cyclone sample mill equipped with 0.5 mm mesh screens for the measurement of pasting properties as well as WSI and WAI.

Measurement of pasting properties

The viscosity-related parameters, such as peak viscosity (PV), through (TH), peak time (PT), final viscosity (FV), and pasting temperature (TP) of ground samples, were measured using a Rapid Visco Analyser (model RVA-4, Newport Scientific Co., Australia). Fiqure 1 shows the viscosity-related parameters and temperature profile generated from RVA test. Three grams of ground sample, adjusted to 14% moisture basis, were added to 25 ml distilled water already placed in the RVA canister. A plastic paddle was inserted into the canister and it was manually rotated to break up any lumps and disperse the powdered material. The canister, along with the paddle, was placed in the RVA, and the test was initiated. The sample temperature was equilibrated to 25°C for 1 min; the sample was then subjected to the heating cycle, increasing at the rate of 6.5°C/min to a maximum temperature of 90°C and holding for 5 min at 90°C, followed by the cooling cycle at the rate of 7.2°C/min to a minimum temperature of 25°C. All viscosity values are reported in rapid visco units (RVU).

Water solubility index (WSI) and water absorption index (WAI) of ground samples were determined as described by Mason and Hoseney (1986). A 2.5 g sample of ground product was suspended in 30 ml of water at 30°C. The sample was shaken for 30 min with intermittent agitation on a vortec mixer (Scientific Products, McGraw Park, IL) then centrifuged at 1,000 g for 10 min. The supernaten was dried, and the amount of solubles was expressed as a percent of the original dry sample weight for WSI. The ratio between the total weight of the pellet and the weight of the solids in the pellet is the calculated WAI. All samples were run in duplicate.

Table 1. Barrel temperatures of each zone from feed end to melt end (from zone 1 to zone 4) and die exit temperature

Trial	Extruder Barrel Temperature (°C)				Die Exit Temperature (°C)
	Zone 1	Zone 2	Zone 3	Zone 4	
1	80	90	100	105	110
2	80	90	110	125	135
3	80	100	125	145	160

Table 2. Screw elements[a] used for conveying shear (CS), low shear (LS) and high shear (HS) screw configulations

CS	21 D twins lead screw (TLS), 4 D single LS (SLS)
LS	8 D TLS, 7×30° forward kneading elements (FKE), 8 D TLS, 3×60° FKE, 3×30° reverse KE (RKE), 2 D SLS, 4×60° FKE, 3×30° RKE, 2 D SLS
HS	8 D TLS, 7×30° FKE, 4 D TLS, 4×60° FKE, 4×30° RKE, 2 D TLS, 6×60° FKE, 4×30° RKE, 1 D SLS, 7×90° KE, 2 D SLS

[a]One kneading element = 0.25 D (1 D = 19 mm)

RESULTS AND DISCUSSION

Extrusion of pressed potato and potato-wheat flour mixtures

In preliminary studies, extrusion of raw potatoes using high shear configuration was found unstable with output fluctuations. This appeared to be due to a combination of

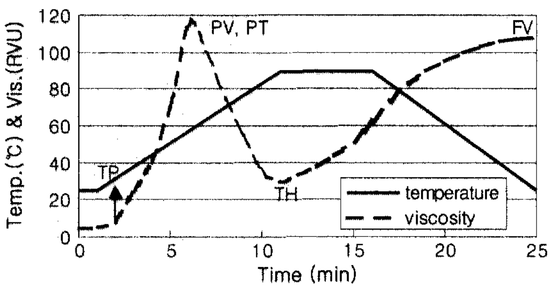

Fig. 1. Viscosity-related parameters and temperature-time profile generated from RVA test.

both the high moisture content of raw potatoes, about 85% on wet basis (w.b.), and the high shear extrusion condition used. The resulting extrudates from the cubes of raw potatoes were only partially cooked, very sticky, and had a high moisture content. With the use of high shear screw configuration, a large number of cell walls might be damaged, allowing starch particles to escape from the potato matrix due to both shearing and heating during extrusion process. Ferdinand *et al.* (1989) reported the difficulty for raw potato extrusion, and then suggested the reduction of its moisture content and use of low shear screw configuration. Raw potatoes were ground and pressed to reduce their moisture content from 85% to 73%. The extrudates from pressed potatoes did expand and attain shape upon exiting the die. However, the shape of extrudates was changed during their accumulation time on a collecting tray, due to their stickiness and moisture content. Della Valle *et al.* (1995) reported the difficulty of extruding potato starch. In their study, this was characterized by high-energy requirements due to high melt viscosity and early melting in the extruder, when compared to other starches. Therefore, in the present study, the pressed potatoes were mixed with wheat flour at mixing ratio of 50%. The moisture content of potato-wheat flour mixture was 53.2% (w.b.). The proximate analyses for pressed potatoes and potato-wheat flour mixture, dried at 40°C, are listed in Table 3. Protein and fat contents of potato-wheat flour mixtures were higher than those of pressed potato due to relatively higher protein and fat contents of wheat flour compared to pressed potato. The extrudates made from potato-wheat flour mixture expanded, maintained their strand shape, and dried quickly.

Table 3. Proximate analyses of pressed potato and potato-wheat flour mixture feed materials

Component	Pressed potato	Potato-wheat flour mixture
Moisture (%, w.b.)	13.39	11.46
Starch (%, d.b.)	86.56	81.62
Protein (%, d.b.)	1.60	5.24
Fiber (%, d.b.)	7.45	5.57
Fat (%, d.b.)	0.36	5.92
Ash (%, d.b.)	1.03	0.52

Viscosity-related parameters of pressed potatoes

It is generally known that the viscosity curves of potato products increase to peak value due to starch swelling, and then decrease due to rupture and alignment of starch structure by heating. Upon cooling, the viscosity increase again due to re-association between starch molecules (Newport Scientific, 1995). Viscosity-related parameters (PV, TH, PT, FV, and TP) of non-extruded and extruded pressed potato products are listed in Table 4. The PV value of non-extruded pressed potato was 653.34 RVU at 10.97 min, and the TH, FV and TP values were 411.50 RVU, 795.71 RVU and 66°C, respectively. These values decreased after extrusion processing ($P<0.05$). This result indicated that the water-binding capacity of starch decreased but water solubility increased due to modification of starch molecular structure during extrusion processing. Davidson *et al.* (1984) observed that extrusion processing contributed to a decrease in intrinsic viscosity (as PV) of wheat starch. The TH value of pressed potatoes, which is hot past viscosity value, decreased after extrusion processing ($P<0.05$) due to more rupture of starch structure degraded by extrusion processing.

The PV, TH, FV, and TP values of extruded pressed potato products decreased significantly as die exit temperature increased from 110 to 160°C ($P<0.05$, refer Table 4). At higher temperatures, mechanical degradation was less pronounced as the viscosity decreased, whereas the kinetics of thermal degradation became more favorable. Mason and Hoseney (1986) found that hot paste viscosity of extruded wheat starch was negatively influenced by die exit temperature and an interaction between screw speed and barrel temperature. This result agreed with the decrease of PV values of extruded pressed potato products with increasing die exit temperature in the current study.

An empirical model was applied to develop the equations for predicting the PV and FV values of extruded pressed potato products. The Arrhenius equation was used to incorporate the effect of die exit temperature on the PV and FV values.

$$PV(\text{or } FV) = A \cdot \exp\left(\frac{B}{T}\right)$$

Table 4. Viscosity-related parameters[a] of pressed potato feed material (control[b]) and extruded pressed potato products

Screw Conf.[c]	Die Exit Temperature (°C)	PV (RVU)	TH (RVU)	PT (min)	FV (RVU)	TP (°C)
–	Control	653.34a	469.79a	10.97a	795.71a	66.18a
CS	110	427.05b	120.62b	7.77b	312.96b	42.35b
CS	135	318.71c	76.67c	7.50b	215.58c	27.70cd
CS	160	229.03d	67.16d	7.25c	169.21d	25.45d

*Values followed by the same letter in the same column are not significantly different ($P<0.05$).
[a] PV: Peak viscosity, TH: Through, PT: Peak time, FV: Final viscosity, TP: Pasting temperature.
[b] Pressed potatoes dried at 40°C using an oven.
[c] Screw Conf.: Screw Configuration, CS: conveying shear.

where PV is the peak viscosity (RVU), FV is the final viscosity (RVU), T is the absolute temperature (K), and A and B are constants. The resulting equations and regression correlation coefficients (R2) are given below.

$$PV = 1.888\exp\left(\frac{2083.639}{T}\right),\ R^2 = 0.992$$

$$FV = 1.477\exp\left(\frac{2047.065}{T}\right),\ R^2 = 0.987$$

Figure 1 shows the calculated and measured PV and FV values of pressed potato products extruded using a conveying screw configuration without paddles. The calculated values generally were within 10% of the measured values of peak viscosity and final viscosity.

Viscosity-related parameters of potato-wheat flour mixtures

The PV value of non-extruded potato-wheat flour mixtures was 506.97 RVU at 12.95 min, and the TH, FV and TP values were 411.69 RVU, 880.31 RVU and 67.88°C, respectively (refer Table 5). The PV, TH, FV, and PT values of extrudates by using a given screw configuration, decreased significantly as die exit temperature increased from 110 to 160°C ($P<0.05$, refer Table 5). The PV and FV values of potato-wheat flour mixture products were lower than those of pressed potato products at a given die exit temperature. Published reports have indicated that initial peak viscosity (as PV) and cold paste viscosity (as FV) of extruded wheat and potato flour blends (Bhattacharya *et al.*, 1999) and cold (as FV) and cooked viscosities (as PV) of extruded corn starch (Owusu-Ansah *et al.*, 1983) all increased with increases in moisture content of the feed. In the current study, the addition of wheat flour might contribute to decreases in the PV and FV values of the potato-wheat flour mixture products relative to those of pressed potato products. The PV, FV, and PT values of extrudates using high shear screw configuration were lower than those of extrudates using low shear screw configuration for each given extrusion condition. This result may have accounted for the higher shear and longer residence time of high shear screw configuration. Anderson *et al.* (1969) reported that reducing shear by using a screw with lower compression ratio increased final paste viscosity of extruded corn grits. This result agreed with the decrease in PV, TH, and FV values of potato-wheat flour products with increasing shear in this study.

Water solubility index and water absorption index

The WSI and WAI of extruded and non-extruded potato products are listed in Table 6. The WSI and WAI values of the non-extruded pressed potatoes and potato-

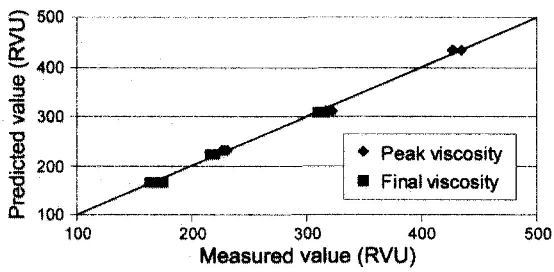

Fig. 2. Predicted and measured values of peak and final viscosities of extrudates made from pressed potatoes.

wheat flour mixtures were 2.30%, 4.55%, 3.35 and 2.32, respectively, and both increased significantly after extrusion ($P<0.05$). The non-extruded pressed potatoes and potato-wheat flour mixtures dried at 40°C did not absorb water at room temperature, whereas extruded products absorbed water rapidly to form a paste at room temperature during the RVA test. This paste is formed by solubilized macromolecules but also includes particles swollen by water (Colonna *et al.*, 1989). Chiang and Johnson (1977) reported that some hydrolysis of starches might occur during extrusion of cereal starches and grits.

Mechanical and thermal energy inputs during extrusion induce change in the physical properties of an extruded substance, which affect functionality such as water solubility. WSI is frequently used by industry since it can be determined quickly and has been linked to important product characteristics (Anderson *et al.*, 1969; Mercier and Feillet 1975). Colonna *et al.* (1989) reported that WSI might be related to the quantity of water soluble molecules, which can be separated quite easily from each other because of limited entanglements. The WSI value

Table 5. Viscosity-related parameters[a] of potato-wheat flour mixture feed material (control[b]) and extruded potato-wheat flour mixture products

Screw Conf.[c]	Die Exit Temperature (°C)	PV (RVU)	TH (RVU)	PT (min)	FV (RVU)	TP (°C)
–	Control	506.97a	411.69a	12.95a	880.31a	67.88a
HS	110	278.90b	51.36b	4.76b	157.56b	25.12b
HS	135	131.42c	29.30c	3.47c	114.67c	25.05b
HS	160	105.27d	24.39d	1.61d	94.05d	25.02b
LS	110	332.97e	47.17e	5.82e	164.31b	25.10b
LS	135	159.94f	33.42f	4.27b	124.91c	25.08b
LS	160	118.36g	29.53c	3.03c	109.39e	25.07b

*Values followed by the same letter in the same column are not significantly different ($P<0.05$).
[a] PV: Peak viscosity, TH: Through, PT: Peak time, FV: Final viscosity, TP: Pasting temperature, Values followed by the same letter in the same column are not significantly different ($P<0.05$).
[b] Potato-wheat flour mixtures dried at 40°C using an oven.
[c] Screw Conf.: Screw Configuration, HS: high shear, LS: low shear.

Table 6. Water solubility index[a] (WSI) and water absorption index[a] (WAI) of feed materials (control[b]) and extrudates

Screw	Temperature	Pressed potato		Potao-wheat flour mixture	
Conf.[c]	(°C)	WSI (%)	WAI	WSI (%)	WAI
–	Control	2.30a	3.35a	4.55a	2.32a
CS	110	11.89b	6.26b		
CS	135	13.72c	7.58c		
CS	160	14.86d	9.64d		
HS	110			13.09b	8.88b
HS	135			14.59c	10.36c
HS	160			17.74d	10.89c
LS	110			13.03b	9.19b
LS	135			16.86e	10.09c
LS	160			17.80d	10.57c

[a]Values followed by the same letter in the same column are not significantly different ($P<0.05$).
[b]Potato-wheat flour mixtures dried at 40°C using an oven.
[c]Screw Conf.: Screw Configuration, CS: conveying shear, HS: high shear, LS: low shear.

for pressed potato and potato-wheat flour mixture products increased significantly from 11.89% to 14.86% and from 13.03% to 17.80%, respectively, as die exit temperature increased from 110 to 160°C ($P<0.05$). The increase in WSI with increasing die exit temperature was in agreement with other researchers who have noted that the WSI value of various starches (Mercier and Feillet, 1975), corn starch (Owusu-Ansah *et al.*, 1983), corn grits (Anderson *et al.*, 1969), and potato starch (Mercier, 1977) increased as extrusion temperature increased up to 250°C.

The WAI values of pressed potato and potato-wheat flour mixture products increased significantly from 6.26 to 9.64 and from 8.88 to 10.89, respectively, as die exit temperature increased from 110 to 160°C ($P<0.05$). The WAI values of corn grits (Anderson *et al.*, 1969; Conway, 1971), rice (Mottern *et al.*, 1969; Hennesey *et al.*, 1971; Spadaro *et al.*, 1971), various starches (Mercier and Feillet, 1975), wheat, rye, barley, and oat flour (Olkku, 1981), and wheat semolina (Kim and Rottier, 1980) reached maxima at extrusion temperature of 180-200°C. A reduction in WAI was observed at higher temperatures due to intense starch degradation in corn grits (Anderson *et al.* 1969). Water absorption index was originally developed as a measurement for the swelling power of starch. In the current study, as die exit temperature increased, the WAI values of pressed potato and potato-wheat flour mixture products increased, whereas their TP values decreased (Tables 4 and 5). Colonna *et al.*, (1989) reported that WAI correlated well with cold-paste viscosity (as FV) because only depolymerized starch granules absorbed water at room temperature and swelled, creating increased viscosity. It appears that the higher the extrusion temperature, the higher the degree of depolymerization of starch, as reflected in the high WAI and WSI values and the low PV and TP values (Tables 4 and 5). Thus, it should be possible to use extrusion temperature to manipulate the degree of depolymerization of extruded potato starch for specific usage, such as in fillers of pharmaceutical, pudding, fish feed, or other products.

Conclusions

Reduction in the moisture content of potato feed materials and use of conveying shear screw configuration of the extruder allowed development of an extrusion dehydration and starch depolymerization process of fresh potatoes. The extruded products from pressed potato and potato-wheat flour mixture were quite different from their respective non-extruded feed materials in terms of the properties evaluated in the current study. The RVA parameters of pressed potato and potato-wheat flour mixture extrudates decreased significantly as die exit temperature increased. Empirical equations were derived to predict peak viscosity and final viscosity for the pressed potato products at the different die exit temperatures studied. The WSI and WAI values of pressed potato and potato-wheat flour mixture extrudates increased significantly as die exit temperature was increased. This process appears to allow development of customized starch products that will be suitable as ingredients in a variety of value-added products.

REFERENCES

AACC. 2000. *Approved Methods of the AACC*. 9th Ed. St. Paul, MN

Anderson, R.A., H.F. Conway, V.F. Pfeifer and E.L. Griffin, Jr. 1969. Gelatinization of corn grits by roll- and extrusion-cooking. *Cereal Sci. Today* **14**: 4-7, 11-12

AOAC. 1995. *Official Methods of Analysis*. 15th Ed. Arlington, VA

Bhattacharya, S., M.L. Sudha and A. Rahim. 1999. Pasting characteristics of an extruded blend of potato and wheat flours. *J. Food Eng.* **40**: 107-111

Chiang, B.Y. and J.A. Johnson. 1977. Gelatinization of starch in extruded products. *Cereal chem.* **54**: 436-443

Colonna, P., J. Tayeb and C. Mercier. 1989. Extrusion cooking of starch and starchy products. In: Extrusion cooking. C. Mercier, P. Linko and J.M. Harper (eds.). AACC, St. Paul, MN. pp. 247-320

Conway, H.F. 1971. Extrusion cooking of cereals and soybeans. *Food Prod. Dev.* **5**: 14-17, 27-29

Davidson, V.J. 1992. The rheology of starch-based materials. In: *Food extrusion science and technology*. J.L. Kokini, C.T. Ho and M.V. Karwe (eds.). Marcel Dekker, New York. USA. pp. 263-275

Davidson, V.J., D. Paton, L.L. Diosady and G. Larocque. 1984. Degradation of wheat starch in a single screw extruder: characteristics of extruded starch polymers. *J. Food Sci.* **49**: 453-458

Della Valle, G., Y. Boche, P. Colonna and B. Vergnes. 1995.

The extrusion behaviour of potato starch. *Carbohydr. Polym.* **28**: 255-264

Ferdinand, J.M., A.R. Kirby, A. Senouci and A.C. Smith. 1989. The extrusion cooking of potato products. In: *Process engineering in the food industry: developments and opportunities.* R.W. Field and J.A. Howell (eds.). Elsevier Applied Science, London. UK. pp. 59-75

Hennesey, G.R., M.F. Stranabury and R.M. Persell. 1971. USDA creates nutritive functional products. *Food Eng.* **43**: 71-74

Kim, J.C. and W. Rottier. 1980. Modification of Aestivum wheat semolina by extrusion. *Cereal Food World* **25**: 62-64, 66

Lawton, B.T., G.A. Henderson and E.J. Derlatka. 1972. The effect of extruder variables on gelatinization of corn starch. *Can. J. Chem. Eng.* **50**: 168-172

Maga, J.A. and M.R. Cohen. 1978. Effect of extrusion parameters on certain sensory, physical and nutritional properties of potato flakes. *Lebensm.-Wiss. U. Technol.* **11**: 195-197

Mason, W.R. and R.C. Hoseney. 1986. Factors affecting the viscosity of extrusion-cooked wheat starch. *Cereal Chem.* **63**: 436-441

Mercier, C. 1977. Effect of extrusion cooking on potato starch using a twin screw French extruder. *Starch* **29**: 48-52

Mercier, C. and P. Feillet. 1975. Modification of carbohydrate components by extrusion-cooking of cereal products. *Cereal Chem.* **52**: 283-297

Mottern, H.H., J.J. Sapadaro and A.S. Gallo. 1969. Cooking-extrusion of rice. *Food Technol.* **23**: 567-574

Newport scientific. 1995. Operation manual for the series 4 Rapid Visco Analyser. Newport Scientific Pty. Ltd., Australia

Olkku, J. 1981. Extrusion processing. A study in basic phenomena and application of food analysis. In: *Developments in food preservation.* S. Thorne (ed.). Elsevier Applied Science, London. UK. pp. 791-794

Owusu-Ansan, J., F.R. Van De Voort and D.W. Stanley. 1983. Physicochemical change in cornstarch as a function of extrusion variables. *Cereal Chem.* **60**: 319-324

Ryu, G.H., P.E. Neumann and C.E. Walker. 1993. Pasting of wheat flour extrudates containing conventional baking ingredients. *J. Food Sci.* **58**: 567-573

Spadaro, J.J., H. H. Mottern and A.S. Gallo. 1971. Extrusion of rice with cottonseed and peanut flours. *Cereal Sci. Today* **16**: 238-240, 261

Walker, C.E., A.S. Ross, C.W. Wrigley and G.J. McMaster. 1988. Accelerated starch-paste characterization with the rapid visco-analyzer. *Cereal Foods World* **33**: 491-494