This is to certify that the

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TWIN SCREW EXTRUSION OF TEFF FLOUR

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ABSTRACT

TWIN SCREW EXTRUSION OF TEFF FLOUR

By

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Teff (*Eragrostis teff*) is a small seeded millet-like cereal grain. Teff is one of the exotic grains appearing in health food stores in the U.S.A. Teff flour was successfully extruded with a ZSK-30 co-rotating twin-screw extruder. A wide range of processing variables were considered: feed moisture content (20-30%), barrel temperature (125-175°C), and screw speed (100-300 rpm). Effects of varying process variables on extrudate quality (expansion ratio, bulk density, water absorption index, water solubility index, product moisture content, and color) and extruder response variables (percent torque, specific mechanical energy, die temperature, and die pressure) were investigated. Results of the study were analyzed using response surface methodology. Second order polynomials were computed to model the measured process and product variables. The resulting regression equations were used to generate response surfaces.

The overall results show that teff flour can be processed using a twin-screw extruder to produce product properties similar to other extruded products currently used in the food industry, and the calculated second order polynomials are sufficiently accurate

and valuable for predicting properties of teff extrudates and extruder response with in the range of variables considered.

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NOMENCLATURE

'a'	Color parameter
'b'	Color parameter
B	Axial distance between the flights (m)
BD	Bulk Density (kg/m^3)
C	Center line distance between screws (m)
D_b	Internal diameter of the barrel (m)
DP	Die pressure (kPa)
DT	Die temperature (°C)
e	Flight width perpendicular to the flight (m)
ER	Expansion ratio
E(t)	Exit age distribution of flow
F(t)	Cumulative residence time distribution
H	Flight height (m)
$H(\theta)$	Channel depth (m)
HTST	High temperature short time
K	Consistency coefficient ($Pa \cdot s^n$)
L	Fill length (m)
'L'	Color parameter

L_D	Length of the die channel (m)
MC	Moisture content (%wb)
n	Flow behavior
N	Screw speed (rpm)
P	Number of parallel flights (thread starts) in a screw
ΔP	Pressure rise (MPa)
PMC	Product moisture content (% wet basis)
Q	Flow rate, extruder output (kg/h)
Q_D	Flow rate in one die channel (kg/h)
r	Screw radius (m)
R_D	Die channel radius (m)
R_s	Outer radius of screw (m)
RSM	Response surface methodology
S	Screw pitch (m)
SME	Specific mechanical energy (kJ/kg)
t_c	Residence time in the conveying section (s)
t_i	Residence time for a screw element (s)
t_m	Residence time in the melt pumping section (s)
T	Temperature (°C)
T_{av}	Average residence time (s)
%T	Percent torque
V_m	Volume of one chamber (m^3)

W	Perpendicular distance between the flights along the helical path (m)
WAI	Water absorption index (g/g)
WSI	Water solubility index (g/g)
x_i	Coded design variable
X_c	Actual value of experimental center point of X_i
ΔX_i	Unit change of variable X_i
Z	Axial distance along the length of the screw (m)
α	Drag flow geometry factor (m^3)
β	Pressure flow geometry factor (m^4)
β_i	Coefficient (empirical parameter)
θ	Angle of rotation (rad)
ϕ	Angle of helix (rad)
δ_f	Distance between the crest of screw flight and the inner surface of the barrel (m)
μ	Apparent viscosity (Pa·s)
η	Response variable

CHAPTER I

INTRODUCTION

Eragrostis teff, called teff in the official language of Ethiopia, Amharic is a small seeded millet-like cereal grain indigenous to Ethiopia. The cereal teff constitutes an important part of the staple diet of Ethiopians. The seeds of teff grain are very small (≤0.002 g or less than 1.5 mm in length). As in other small-seeded cereals, the embryo, which is rich in protein and lipid, occupies a relatively large proportion of the grain (Parker et al., 1989) and produces nutritious flour upon milling.

The total global production of small millets including teff, is many times less than that of the three major cereals- wheat, rice, and corn. However, the small millets are used as a major food staples under conditions where the major cereals are not adapted or as a complement to the major cereals and legumes. The minor millets have been well described by Rachie (1975) and Hulse et al. (1980). As an important food crop grown in Ethiopia, and one which possesses characteristics enabling it to maintain its yield even under adverse agronomic conditions, teff plays an important role in Ethiopia's economy.

Teff is one of the exotic grains appearing in health food stores in the U.S.A. Teff is being used as a source of protein (6 to 10%), calcium, fiber and iron for nutrition minded Americans. The amino acid analysis of the cereal teff was made by Jansen et al.

(1962) and Lester and Bekele (1981). Its appealing, sweet and molasses-like flavor makes teff a perfect alternative grain for people allergic to the gluten in wheat and related problems (Sokolov, 1993).

1.1 Economic Significance of Teff

Teff (*Eragrostis teff*) is an important cereal cultivated and utilized in Ethiopia. As shown in Table 1.1 teff occupies about 29% of the cultivated land under cereals while sorghum 18%, barley 18%, corn 17%, wheat 13%, and finger millet 5%.

The significant contribution of teff to Ethiopia's economy may be summarized as:

1. It is the crop that is produced on the largest area used for cereal production in Ethiopia with an annual production of 1.2 million tones;
2. The most important cereal to farmers, bringing the highest price in the market as compared to any other cereal;
3. The most consumer preferred grain for making *injera* (bread);
4. Agronomically versatile and reliable cereal crop even under adverse conditions such as low moisture stress, water logging and not attacked by storage pests such as weevils.

Table 1.1 Estimated area under cultivation and production of major crops in Ethiopia, 1977-78 to 1985-1986.

	Hectarage ('000)			Production ('000)		
Crop	Range	Mean	%	Range	Mean	%
Wheat	487-779	610	13	429-917	641	12
Barley	796-927	850	18	690-1168	910	18
Corn	653-947	830	17	948-1603	1205	23
Finger millet	215-238	227	5	187-240	203	4
Sorghum	726-1026	865	18	507-1643	1069	21
Teff	1296-1513	1363	29	912-1426	1141	22

Sources: Land use planning and regulatory department 1982. Vol. 1, Ministry of Agriculture, Addis Ababa.
Central Statistical Authority, 1987. Time series data on area production and yield of major crops, 1979/80 to 1985/86. Statistical bulletin 56, CSA, Addis Ababa.

1.2 Teff Products

Teff grain is used for making several types of flat breads that form the basic traditional diet of Ethiopians. Teff is also used, to a lesser extent, in porridge, tella (local beer), and katikalla (local spirit). Teff is not suitable for making leavened bread because the flour lacks gluten, but when available, wheat and other cereal flours may be mixed with teff flour for a variety (Stewart and Asnake, 1962). Recently, the Natural Resources Institute of U.K. found that at least 20% hammer-milled teff flour can be added to the wheat flour and excellent bread produced.

The most popular type of flat bread is *injera*, a flexible, spongy, pancake-like fermented and baked product perforated with 'eyes'. In the traditional process of making *injera* the dough is prepared by mixing teff flour with water and allowing the endogenous flora to perform fermentation, or *irsho*, a thin paste saved from the previous fermentation may be added as a starter culture. While preparing for baking, the liquid that settled on the dough at the end of the primary fermentation is discarded. Then, *absit*, a boiled portion of the fermented dough is added to the bulk dough to initiate the secondary fermentation which usually lasts about one hour. The fermented dough, which has the consistency of batter, is poured onto the hot oiled surface of the pan or *metad*, which is a round smooth clay griddle. The *metad* is then covered with a tight-fitting lid to retain the steam and baked for a few minutes to produce *injera*.

In bread made from wheat flour, the endosperm stored proteins form a continuous gluten network, in which starch granules and gas bubbles are held (Bechtel et al., 1978). However, according to Parker et al. (1989), teff storage proteins play no part in the structural integrity of *injera*. However, they may add to the texture and the major contributor to the *injera* matrix is gelatinized starch. This type of steam-leavened starch matrix is also found in commercially-produced wafers made from wheat flour. In wafer production, as in the cooking of *injera*, it is important that batter-like dough have a higher water content, that a steamy atmosphere be maintained throughout the cooking period, and that heat be efficiently transferred from the cooking surface (Stevens, 1976).

As compared to other cereals, information on processing of small millets like teff for food and industrial uses is very limited. However, Malleshi (1989) indicated that small millets can be processed to diversify their uses and to improve their nutritive value and consumer acceptability. Milled or decorticated millets could be used in preparation of flakes, quick-cooking cereals, or extruded products.

Extrusion is an efficient food processing method in terms of energy consumption, because it combines a number of unit operations like mixing, heating, shearing, and texturization. The high temperature short time extrusion cooking has proven to achieve microbiological safety and stability, without running the risk of overcooking, discoloration or damage to nutritional or functional properties (Smith and Ben-Gera, 1980). Applications of extrusion cooking include the production of pregelatinized and modified starches, expanded cereals and confectionery products, bread crumbs, biscuits, crackers, baby foods, chewing gum, pet foods and texturized protein foods.

Extrusion cooking of cereals has been studied by many researchers including: cereal starches and corn semolina by Mercier and Feillet (1975); corn grits by El-Dash et al. (1983), Owusu-Ansah et al. (1983, 1984); corn, rice, and potato flours with whey protein concentrate by Kim and Maga (1987); sorghum by Phillips and Falcone (1988); wheat flour, rye flour, oat grits and whole grain barley by Vainionpaa (1991); degerminated yellow corn meal by Halek and Chang (1991); rice flour by Grenus et al. (1993).

As compared to the single-screw extruders, modern twin-screw extruders are more intricate, offer better control of internal shear and residence time of heat sensitive materials, and can be used for processing very low-moisture products to minimize drying requirement (Harper, 1981). Although twin-screw extruders have a variety of designs, the co-rotating, intermeshing screw type has gained the widest acceptance.

1.3 Discussion of the Need

There is a growing interest in producing and selling this mini-grain in the U.S.A. Wayne Carlsol of Caldwell, Idaho and Wokinesh Spice Blends, Inc. of Oshtemo, Michigan are growing and selling teff as a cash crop.

In the modern world, snacks and extruded products are becoming increasingly popular and important. Ms. Rebecca T. Wood of Caldwell, Idaho has prepared ten recipes for cooking with teff: teff waffles, jalapeno teff fillets, great chocolate cake, chocolate mint refrigerator cookies, moroccan chicken stew, muffins, teff banana bread, double-teff butter-pecan tea cakes, teff breakfast cereal, and date cake. Such encouraging start may help promote the use of teff in other foods as well.

Extrusion cooking of teff could produce a healthier breakfast cereal of acceptable taste and nutritional value. The cereal may possibly be used by people who suffer from grain allergies. In Ethiopia, the production of teff is currently limited to domestic consumption. If teff can be used as an alternative to substitute some of the wheat or other cereals, this may favor agricultural development and commerce in its country of origin (and could potentially do the same in other countries).

The effect of raw material on extrusion stability, output and product quality is dependent on the extruder process parameters. In normal cereal extrusion, three variables: water feed rate, barrel temperature, and screw speed are critical to control product characteristics. Extrusion cooking of cereals like wheat, rice, corn, and oats has been widely studied. However, published work on teff-extrusion is non-existent.

1.4 Objectives

The main objective of this study was to examine the extrudability of teff flour. The specific objectives of this work were:

1. To study the effects of primary extrusion processing variables: feed moisture, barrel temperature and screw speed on extrusion of teff flour;
2. To study the functional properties of extrudates;
3. To study the relation between product properties and the extrusion processing parameters used.

CHAPTER II

REVIEW OF LITERATURE

2.1 Extrusion Cooking

2.1.1 Definition of Extrusion

Extrusion has been defined as a process that involves forcing a material to flow under a variety of controlled conditions and to pass through a shaped hole or slot at a predetermined rate. Extrusion can be used for different functions such as mixing, cooking, forming, puffing depending on the extruder design and the process conditions. Extrusion is used in the production of pasta, breakfast cereals, biscuits, crackers, crisp breads, baby foods, snack foods, confectionery items, chewing gum, texturized vegetable proteins, modified starches, pet foods, dried soaps, and dry beverage mixes (Linko et al., 1983).

Extruders can be categorized into one of three main types: piston extruders, roller extruders, and screw extruders (Thorz, 1986). Piston extruders are mainly used for forming. They consist of a single or a group of pistons which deposit quantities of materials onto a conveyor. Roller extruders consist of two counter-rotating rolls with smooth or profiled surfaces. They are also used as forming machines. Screw extruders have single, twin, or multiple screws rotating with in a stationary barrel to push the material forward through a die.

Early applications of extrusion to food date back to the mid- to late 1800's to the production of sausage and processed meats. A piston extruder to stuff casings, and a simple food chopper having a single screw to force soft foodstuffs through a die plate were used for these applications (Harper, 1980). Another early application of food extrusion to food processing was in pasta production following the invention of a hydraulically operated, cylindrical ram macaroni press. In 1935, the first single-screw extruder, the pasta press was applied in the food industry as a continuous system. The pasta press served the purposes of ingredient mixing, dough forming and forcing it through dies creating the desired pasta shapes.

By the late 1930's the ready-to-eat (RTE) breakfast cereal industry was using extrusion to form bite-size cereal shapes from hot, precooked cereal dough. General Mills, Inc. was the first to introduce an extruded RTE cereals using this process (Harper, 1981). Other extruders having both cooking and forming capabilities were introduced in the late 1940's. These included the cooker extruder, developed to pre-cook corn and soybean for use in animal feeds, and the collet extruder. Collet extruders were introduced in 1946 for producing highly expanded snack products from grain based ingredients (Hess, 1973). In the sixties, single-screw extruders became popular for pre-cooking starches, texturizing soya proteins and for direct expansion of breakfast cereals.

One of the important characteristics of cooker extruder is the possibility of high temperature short time (HTST) cooking (Harper, 1978). Smith and Ben-Gera (1980) described HTST extrusion cooking as the most versatile and most economical thermal processing system. This can be justified because of many conversions that could be carried out at lower moisture contents which lowers the drying costs for gelatinized or texturized products at shorter residence times. In HTST cooking, controlled condition of cooking are provided by keeping lower processing temperature during processing the dough and applying elevated product temperature during the few seconds of the dwell time.

Examples of HTST product applications include texturized vegetable proteins, RTE cereals, beverage powders, biscuits, weaning and baby foods, dry pet foods. Other applications include inhibition of microorganisms without overcooking which otherwise promote spoilage, inactivation of antinutritional factors such as trypsin inhibitor in soybeans, and denaturation of enzymes which are responsible for rancidity.

Johnston (1979) has discussed the technical fundamentals of HTST extrusion cooking equipment. The methodologies of HTST extrusion cooking were discussed by Smith and Ben-Gera (1980).

2.1.2 Advantages of Extrusion Cooking

Extrusion cooking has become one of the most important food processing methods because of its many advantages (Harper, 1978) which include:

Energy efficiency - continuous extrusion cooking completes a number of unit operations such as mixing, heating, shearing, texturizing in a single machine and the cost of drying the extrudate is also lower since extrusion can be carried out at low moisture content.

Flexibility - with appropriate changes in process and system parameters of the extrusion process, various kinds of food products having a wide range of forms, shapes, densities, and textures can be made with the same extruder.

Cost effectiveness - includes savings in energy, labor, investment cost and floor space.

Improved product functional characteristics - extruders are used to improve functionality such as gelatinization of starches and the modification of protein textures and structures to control optimal growth inhibitors and anti-nutritional factors to produce cleaner, microbiologically safer and more stable food products.

Improved sanitation - extrusion cookers can be easily disassembled for cleaning, so that poor quality flavors are not to be developed in processed foods.

2.1.3 Single-Screw Extruders

In order to understand the twin-screw extrusion process, one must begin with single-screw extruders. The single screw extruder has been widely used in the production of various food products. Basically a single-screw extruder may be regarded as a friction pump, as it relies entirely on friction between the material being processed and the barrel wall to convey material (Clark, 1978).

The screw is the key element of the single screw extruder, as its geometry influences the unit operation of the extruder (Harper, 1978). It consists of a helical flight wound around a metal shaft enclosed within a cylinder barrel. The geometry of the screw barrel assembly is shown in Figure 2.1. D_b is the internal diameter of the barrel. The flight height (H) is the distance between the screw root and internal surface of the barrel,

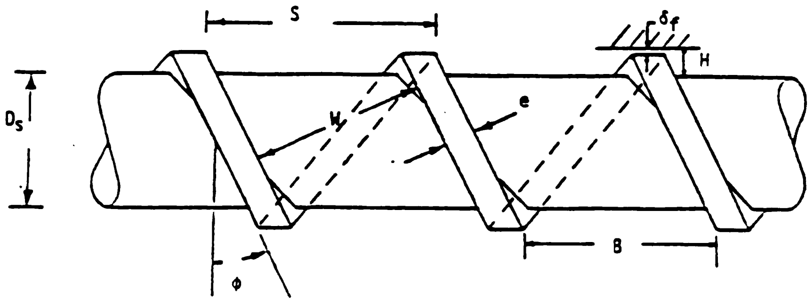

Figure 2.1 Single Flighted Extruder Screw (White, 1991)

the radial clearance (δ_f) is the distance between the crest of the screw flight and the inner surface of the barrel, the flight width perpendicular to the flight is e, the axial distance between the flights is B. The perpendicular distance between the flights along the helical path of the screw is W. The angle of helix is ϕ , and it is the angle the helical flight makes with the vertical. The axial distance of one full turn of the screw (screw lead or pitch) is S. The helix angle ϕ will vary with radius because the pitch S is constant and ϕ is defined by relating S to the circumference through:

$$S = 2\Pi r \tan\phi(r) \tag{1}$$

The helix angle decreases as one proceeds from the screw root to the barrel. The pitch S can vary along the length of the screw and is related to e and B (White, 1991) as follows:

$$|S| = P\left(B + \frac{e}{\cos\phi}\right) \tag{2}$$

Where P is the number of parallel flights in a screw. Absolute value is used because backward pumping screws have negative helix angles and pitch S.

The typical single-screw extruder is shown in Figure 2.2. The single-screw extruder has three processing zones: the feed zone, the kneading zone, and the final metering zone (Matson, 1982; Hauck, 1985a). The feed zone has deep flights or channels to receive and mix the incoming feed ingredients; the kneading zone, having a decreased depth of flights, applies compression, mild shear and thermal energy to the feed; the final cooking zone has very shallow flights which generate high shear causing the temperature of the material to increase rapidly, reaching a maximum before the product is forced through the die (Harper, 1978).

Heat input to the product in extrusion comes from different sources which include steam injection into the extruder barrel, frictional heat developed at the barrel wall and in the die area during rotation of the screw, or heat transfer from a steam jacket encasing the barrel or from a steam quill in a hollow-cored screw. The desired product properties can be produced by controlling several parameters including screw geometry, length of barrel; clearance between the screw and the barrel; die geometry, screw speed, flow rate,

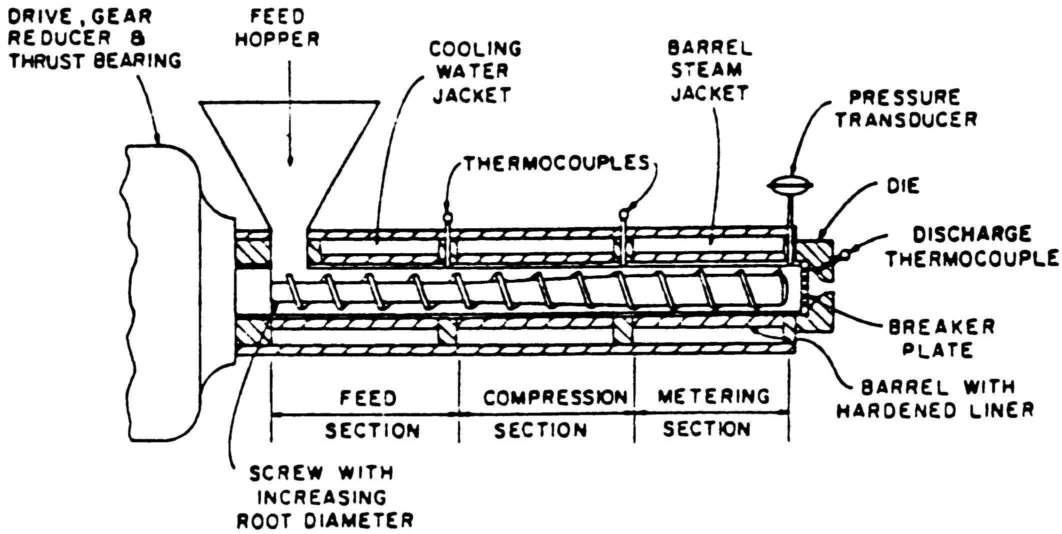

Figure 2.2 Typical Components of a Single-Screw Extruder (Harper, 1978)

moisture content of the feed; and apparent viscosity of the material (Clark, 1978).

2.1.4 Twin-Screw Extruders

Twin-screw extruders include a variety of machines with different processing and mechanical characteristics. Interest in twin-screw extruders is growing mainly because of its greater flexibility in controlling product and process parameters which include: tighter control on product variability; changes in formulation, screw speed, die configuration, narrow residence time distribution, efficient pumping and self wiping features, ability to release steam and/or vent other volatiles, higher process stability, more uniform size and shape of the finished product, improved product color and density; easy access to the screws without disassembling the extruder; ability to process a broad range of formulations; greater thermal and mechanical mixing efficiency; and uniform shear rate profile.

2.1.4.1 Types of Twin-Screw Extruders

Twin-screw extruders can be categorized according to the position of the screws in relation to one another, and to the direction of screw rotation. Extruder screws can be either co-rotating when both screws turn in the same direction; or counter-rotating when the screws turn in opposite directions. Regarding position of the screw, extruders can have intermeshing screws (partially or fully intermeshing) in which the flights of one screw engage the channels of the other screw, or non-intermeshing screws in which the screws do not engage each other's threads.

Twin-screw extruders may also be sub divided based on the flow path of the material. In lengthwise-open extruders, the material moves axially along the barrel toward the die. In crosswise-open extruders, the material moves across the barrel from the channel of one screw to two different channels of the other (Martelli, 1983). Figure 2.3 shows such a classification.

Non-intermeshing twin-screw extruders are described as two single-screw extruders sitting side by side with only a small portion of the barrels in common (Clark, 1978). Neither pumping nor mixing is positive. These extruders rely on friction for extrusion. On the other hand, intermeshing twin-screw extruders are characterized as positive pumping, efficient mixing, and self cleaning. They generally act as positive displacement pumps, forcing material enclosed between the screws to move toward the die by rotation of the screws. The pumping action depends on the screw geometry and occurs independent of the operating conditions.

2.1.4.2 Counter-rotating Twin-Screw Extruders

These extruders are not widely used in the food industry. They are characterized by poor mixing, low capacity and greater positive displacement as compared to co-rotating extruder. Counter-rotating twin-screw extruders are similar to single-screw extruders in that they have high shear stresses at the barrel walls and low stresses in the middle of the channel.

Fully intermeshing counter-rotating twin-screws carry small volumes of material down the barrel with in C-shaped chambers (Martelli, 1983). The material is forced to

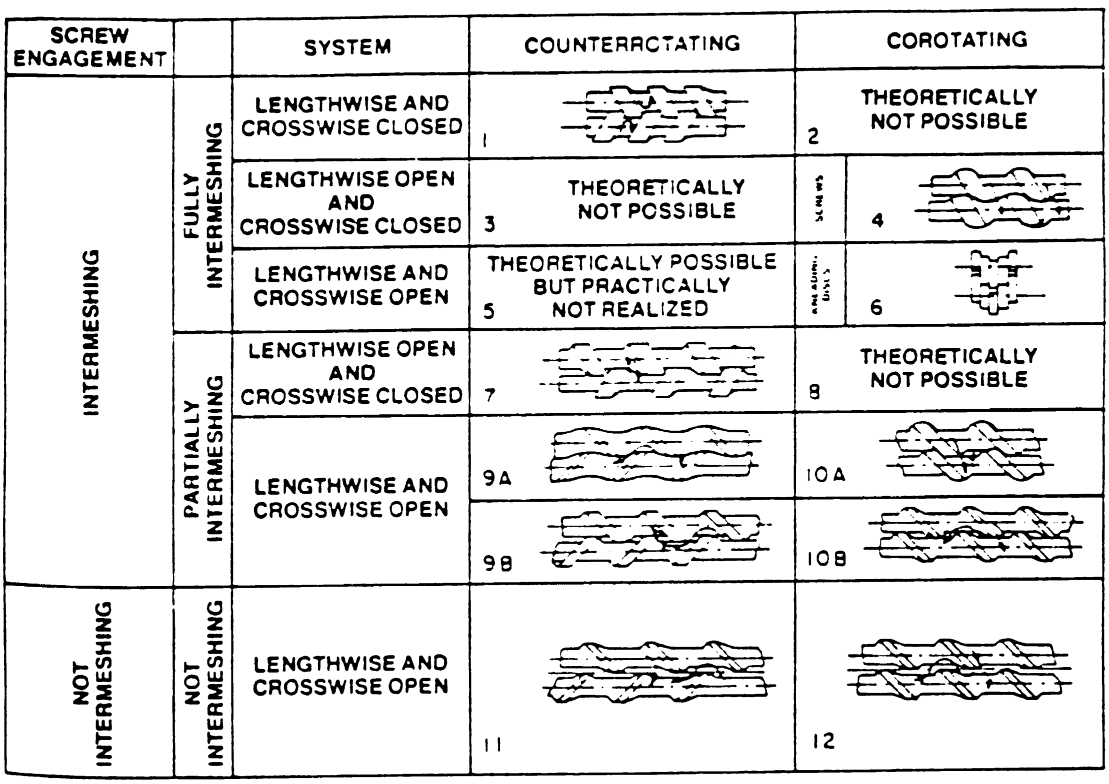

Figure 2.3 Screw Configurations of Twin-Screw Extruder (Ziminski and Eise, 1980)

flow through small mechanical clearances around the flights at the point where the two screws intermesh. The calender effect, created when the crest of one screw rolls off the root of the other, takes place with poor mixing of material from one screw with that of the other. Pressure attributed to the motion of the screws and the calender effect pushes the screws apart causing wear on both the screws and the barrel wall. Therefore, unlike co-rotating screws, counter-rotating screws must be operated at low speeds (Harper, 1992) because the wear increases with the relative speed of the shafts. These extruders are particularly suited for processing relatively non-viscous materials requiring low speeds and long residence times. Examples of such products are gum, jelly, and licorice confectionery (Elsner and Wiedmann, 1985).

2.1.4.3 Co-rotating Twin-Screw Extruders

These are the more commonly used extruders in the food industry. Advantages of this system are its pumping efficiency, good control over residence time distribution, self cleaning mechanisms, and uniformity of processing (Schuler, 1986). The co-rotating screws are better suited for applications which require a high degree of heat transfer but not forced conveyance (Elsner and Wiedmann, 1985).

Intermeshing co-rotating screws transport four to five times more volume of material in open V-shaped chambers as compared to intermeshing counter-rotating screws. Because of the engagement of the screws they also result in a better mixed product. The exchange of the material also contributes, in part, to a uniform shear stress distribution which in turn enhances the mixing and energy efficiency of the process (Hartley, 1984).

Co-rotating screws have a transitional motion in which one crest edge wipes a screw flank tangentially with a constant relative velocity. Because this occurs at a relatively high speed and without producing a calender effect, the screws achieve a more efficient and uniform self-cleaning (Hartley, 1984). Besides, the extruder can be operated at higher screw speeds since no pressure develops to push the screws apart.

The co-rotating twin screws can be fitted with different types of kneading discs to improve the mixing function of the extruder (Hartley, 1984). Figure 2.4 shows food materials being passed from one disk to another to accomplish the kneading action and mixing. The discs can have a forward conveying effect, a neutral effect, or a reverse conveying effect. Forward-conveying discs increase the pressure profile within the channel by pushing the material toward the die. Reverse conveying discs reduce the pressure by delaying the passage of material through the extruder, allowing it to undergo additional processing with improved efficiency of heat transfer through the barrel wall. The pressure can be reduced to atmospheric levels to allow the release or venting of steam or other volatile or to introduce another feed in the downstream portion of the machine (Hartley, 1984).

2.1.4.3.1 Screw Geometry

Intermeshing co-rotating twin screw extruders generally have self wiping profiles for both their screw and kneading disc elements (Figure 2.5). Booy (1978) showed that the channel depth in self wiping screw profile which is continuous and maintains a monotonic second increasing derivative must vary according to:

$$H(\theta) = R_s(1+\cos\theta) - \sqrt{C^2 - R_s^2\sin^2\theta} \quad (3)$$

where R_s is the outer radius of the screw, θ is the angle of rotation of the screw and C is the centerline distance between the screws. For screw elements the angle θ may be expressed in forms of the axial distance along the length of the screw Z:

$$\theta = 2\Pi\left(\frac{Z}{S/P}\right) \quad (4)$$

where S is the pitch and P is the number of thread starts.

2.1.4.3.2 Transport Phenomena

Twin screw extruders are geometrically complex machines. Studies about extrusion technology in the synthetic polymer field has contributed to the understanding of transport phenomena in food extrusion. Therefore, flow models are generally deduced from polymer extrusion.

For co-rotating twin screw extruders, the channel from one screw to the other is widely open (Martelli, 1983; Ollet et al., 1989): the closing of the channel in the intermeshing zones is about 55% for deep screw channel and less (15%) for shallow ones. In polymer extrusion, the model generally used considers a channel with varying restrictions during passage of product from one screw to the other (Wyman, 1975; Booy,

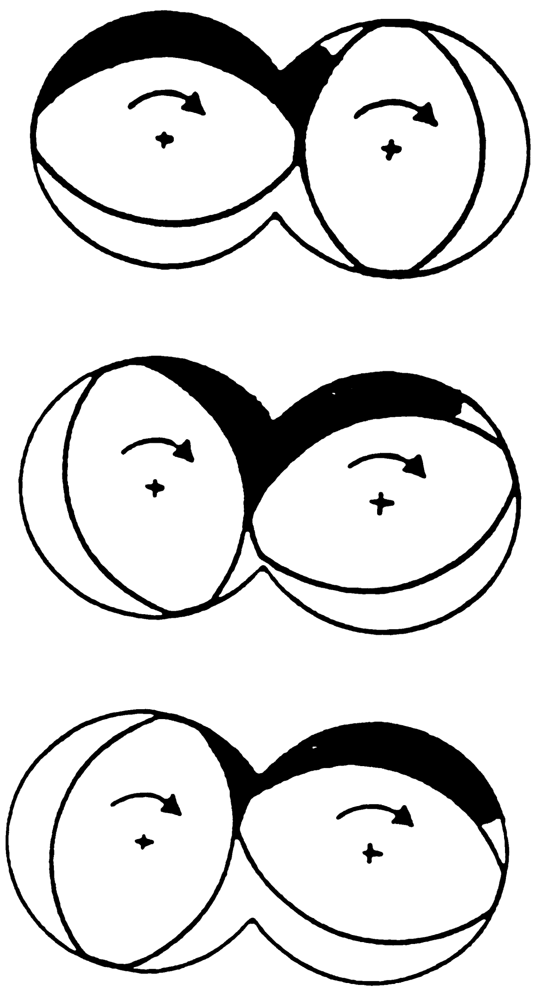

Figure 2.4 Kneading Elements of a Twin-Screw Extruder (Harper, 1991)

1980; Masheri and Wyman, 1980; Denson and Hwang, 1980; Martelli, 1983; Eise et al., 1983; Szydlowski and White, 1987; Wang et al., 1989). For co-rotating twin screw food extruders, however, only a few models covering the whole extruder have been proposed (Yacu, 1984; Tayeb et al., 1988, 1989). The main limitation pointed out in modeling twin-screw food extruders is lack of adequate knowledge about the flow and thermal characteristics of food products.

The following flow model was developed for co-rotating twin-screw extruders (Todd, 1989), and the extruder output, Q, is defined as:

$$Q = \alpha N - \frac{\beta}{\mu} \frac{\Delta P}{L} \tag{5}$$

where N is screw speed, μ is viscosity, ΔP is the pressure rise, L is the fill length, α and β are constants based on screw geometry which needs to be determined experimentally.

Die geometry is an important factor of the volumetric expansion of extruded products. Different types of die designs are available varying in sophistication from single circular die holes to rotating and co-extrusion dies. For a circular die, the pressure-throughput relationship may be computed by using the solution of the Stokes equation (Rauwendaal, 1986), even for pseudoplastic product like corn starch, as studied by Vergnes and Villemaire (1987):

$$Q_D = \frac{n}{3n+1}\left(\frac{1}{2K}\frac{\Delta P}{L_D}\right)^{1/n} R_D^{(3n+1)/n} \qquad (6)$$

where Q_D is the flow rate in one die channel, ΔP is product pressure R_D is the die channel radius, L_D is the length of the die channel, K is the consistency coefficient and n is flow behavior index for power fluids.

2.1.4.3.3 Residence Time Distribution

It is the measure of time the process material spends in the processing equipment. The residence time reveals information about flow patterns, degree of mixing, design of equipment, processing condition, and retention time of the material in the processing device.

Although the study of residence time for extrusion processes has received considerable attention (Pinto and Tadmor, 1970; Todd and Irving , 1969 ; Bigg and Middleman, 1974; Todd, 1975; Janssen et al., 1979; Olkku et al., 1980; Davidson et al., 1983; Colonna et al., Wolf et al., 1986; and Altomare and Ghossi, 1986) there have been no generally satisfactory studies of residence time distribution (RTD) and mixing in intermeshing co-rotating twin-screw extruders (White, 1991).

Levenspiel (1972) defined the exit age distribution E(t) function so that E(t)dt is the fraction at the exit, of flow that has spent a time between t and (t + dt) in a system. The cumulative exit age distribution F(t) function can be obtained by integration to give

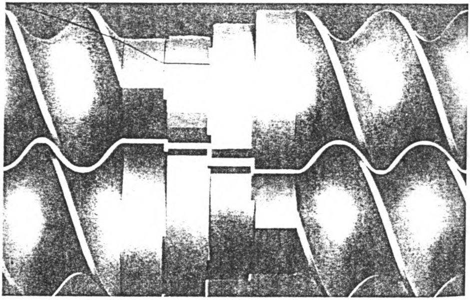

Figure 2.5 Self Wiping Profiles of a Twin-Screw Extruder (Wiedmann, 1991)

a cumulative residence time distribution function.

$$F(t) = \int_0^t E(t)\,dt \qquad (7)$$

The average residence time T of the material in the extruder is calculated as:

$$T_{av} = \int_0^\infty t\,E(t)\,dt \qquad (8)$$

Residence time measurements of most published works were made with a radio tracer with a known behavior. Jager et al., (1988, 1989) and van Zullichem et al., (1988) presented a numerical RTD model to translate the RTD into a mass flow pattern for co- and counter rotating twin-screw extruders.

In the converging section, average residence time is estimated according to the movement of the main layer of material with a plug flow assumption in each section of the screw of a given pitch, the residence time (t_i) can be computed from section length (L), screw speed (N), and screw pitch (S) as:

$$t_i = \frac{L_i}{NS_i} \qquad (9)$$

Where the subscript i refers to different screw elements. The total residence time in the conveying section can be obtained by $t_c = \Sigma t_i$. In sections full of molten material, average residence time can be estimated by using a plug flow model from volume (V_m) and flow rate (Q) as:

$$t_m = \frac{V_m}{Q} \tag{12}$$

2.1.4.3.4 Mixing

Ingen-Housz (1983) describes three types of mixing: axial, dispersive, and distributive. Axial mixing, also called macro mixing is for the whole length of the extruder in an axial direction. Dispersive mixing is the size reduction of the agglomerations present by velocity gradients in the mass flow. In a twin screw extruder dispersive mixing can be found in all sections in which shear is dissipated. Distributive mixing also called laminar mixing is related with the distribution of small volumes of material within the extruder. This is mainly dependent on the leakage flows.

2.1.5 Comparison Between Single- and Co-rotating Twin-Screw Extruders

The characteristics used to compare single- and twin-screw extruders are given by Harper (1991). Single-screw extruders, although they lack the mixing efficiency, process control and product uniformity acclaimed for twin-screw extruders, are more economical to operate and maintain with lower initial capital costs.

Some of the advantages the twin-screw extruder offers include:

Process versatility and control. The output of twin-screw extruder is independent of screw speed (Purvis, 1987) since it is generally operated in starve-fed mode (the screw speed exceeds the feed rate). This enables to produce different product textures from the same formulation with the same screw by changing the screw speed to vary the mechanical shear rate. Twin-screw extruder has a tighter control over product variability because of its ability to approach the desired shear. The efficient pumping action and self wiping features of the twin screws ensure a uniformly processed product and reduced down time. According to Straka (1985), twin-screw extruders are designed to transport material more efficiently in a uniform, continuous stream through the barrel. This uniformity leads to a more uniform shape and size of the finished product.

Flexible machine design. The design of twin-screw extruders which permits easy access to the screws without disassembling the extruder allows screws and barrels to be cleaned in place or the screw configuration to be changed. The twin-screw extruder also has the capability to continue operating when ingredient feed is interrupted, because the screws are self cleaning, however, single-screw extruders shut down completely with short feed interruptions, requiring machine disassembly. The twin-screw extruder can be restarted quickly after shutdown (Rhodes and Olbertz, 1985) without the need to clean dies and screws (Straka, 1985).

Ability to process specialty formulations. The twin-screw extruder can process a broad range of formulations because of its intermeshing screws including some that are difficult for single-screw extruders, such as low-density powders that have low purging ability and sticky material that have higher sugar contents (Straka, 1985). Products having up to

25% fat content can be processed using screw configurations that are not available in the single-screw extruder. The thermal and mechanical mixing efficiency of the twin-screw extruder results in a more consistent product which leaches less fat during handling and storage (Hauck, 1988).

Capital Investment. Considering cost, single screw extruders are superior since they are more economical to operate and maintain. Twin-screw extruders cost 60-100% more than single-screw extruders of equivalent production capacities, and their electrical operating costs are about 1 to 2 times higher than for comparable single-screw extruders (Harper, 1991). These factors may attribute to the widespread use of single screw extruders in the food industry. However, to get a product of consistent quality or to make more unique products it may be important to consider the advantages of twin-screw extruder.

Because of its flexibility, ability to handle a broader range of ingredient moisture and feed materials , the twin-screw extruder is an attractive alternative for food processes requiring cooking and forming (Harper, 1991).

2.1.6 Extrusion Cooking of Cereals and Starch

The functional properties of extruded foods have also been extensively studied leading to several reviews (Rosen and Miller, 1973; Harper, 1979, 1981, 1986; Linko et al., 1981; Bjorck and Asp, 1983; Mercier et al., 1989; Colonna et al., 1987, 1989; Guy and Horne, 1988; Kokini et al., 1991). Influence of extrusion cooking on product qualities have been generally studied and modelled by different researchers including (Gomez and Augilera, 1984; Owusu-Ansah et al., 1984; Bhattacharya and Hanna, 1987a), and some laboratory studies have been carried out on the influence of extrusion processing variables on the texturing of soya protein (Cumming et al., 1972; Maurice et al., 1976; Frazier et al., 1983).

The basic structures of extruded products are formed by transforming and manipulating natural biopolymers, such as those of starch or of certain types of proteins. In the former case the most commonly used materials are cereals like wheat, corn and rice, and potato derivatives, such as flours and granules. Other cereals and starch-rich materials in less common usage include rye, barley, oats, sorghum, cassava, tapioca, buck-wheat, pea flours, and other related materials (Guy, 1994). Extrusion cooking of cereals involves physical and chemical changes such as: mechanical mixing, shearing, and disintegration of discrete entities in the micrometer size range, and molecular changes. These in turn include hydration and swelling of the starch granules, and gelatinization of the starch with loss of crystallinity. These changes have been identified by X-ray diffraction (Mercier et al., 1980), by spectroscopy of starch-iodine complexes (Gomez and Aguilera, 1983), and by enzyme susceptibility (Bhattacharya and Hanna, 1987b). Harper (1981) found out that unbranched amylose diffuses out of the swollen and gelatinized granules and forms complexes with lipid components as shown by the appearance of a characteristic V-type X-ray diffraction pattern (Mercier et al., 1980). The extent of these changes depends on the conditions of moisture content, temperature, and mechanical energy input during extrusion. The molecular changes influence the qualities of the extrudate such as compressive strength, bulk density, and brittleness. Other major changes occurring during the process of starch extrusion are the disruption of the crystalline regions in the granule and possible formation of amylose-lipid complexes (Colonna et al., 1989).

Many analytical methods are being used to reasonably estimate starch damage which can be used to control both the process and product. Starch damage is any structural change giving reduced resistance to the action of amylases (Chiang and Johnson, 1977) and/or thermal dispersion. Criteria based on the functional properties of extrudates appearing after extrusion such as swelling, or increase in solubility are used since extruded products loose their granule integrity and crystallinity.

2.1.6.1 Expansion

Expansion is usually expressed as a ratio between the diameters of the extruded product and the die, which is called expansion ratio (Van Zuilichem et al., 1975; Faubion and Hoseney, 1982a; Vainionpaa, 1991; Bhattacharya and Prakash, 1994). Extrudate expansion has been studied extensively. The two most important factors affecting the expansion ratio are moisture content and extrusion temperature (Mercier and Feillet, 1975; El-Dash et al.,1984; Park,1976). Screw geometry, screw speed, and shear within the extruder are also shown to affect the expansion of starch (Bhattacharaya and Hanna, 1987b). Factors affecting the degree of expansion with single-screw extruders have also been investigated by Van Zuilichem et al. (1975), Mega and Cohen (1978), Faubion and Hoseney (1982a, 1982b), Alvarez-Martinez et al. (1988), and Chinnaswamy and Hanna (1988). Mercier and Feillet (1975), Launay and Lisch (1983), Antila et al. (1983), Owusu-Ansah et al. (1984), and Guy and Horne (1988) have studied expansion with twin-screw extruders.

Starch content has also been related to the degree of expansion. According to Horn (1977) maximum and minimum expansions were obtained for pure starches (500% increase in product diameter), and oil seeds (150-200%), respectively. The amylose-amylopectin ratio is also important in determining properties of starch-based extruded products.

2.1.6.2 Solubility

Water absorption and water solubility are the main functional properties of starch extrudates. Water absorption index (WAI) and water solubility index (WSI) may be used in estimating the suitability of using extruded starchy products in suspensions or solutions.

Water absorption index is the weight of gel obtained per gram of dry sample. It is determined by the method of Anderson et al. (1969) as briefly described in the materials and methods of this paper. Because only damaged starch granules absorb water at room temperature and swell, creating increased viscosity, WAI is found to correlate well with cold-paste viscosity. After reaching a maximum, related to the degree of starch damage, WAI decreases with the onset of dextrinization.

Water solubility index is the percentage of dry matter recovered after the supernatant is evaporated from the water absorption determination (Anderson et al., 1969). WSI is related to the quantity of soluble molecules, which is related to dextrinization. The water solubility of starch increase with expansion, and the stickiness of the extruded starches is related to increased solubility (Colonna et al., 1989). WSI increases with the severity of the thermal treatment in the extruder. WSI has been shown to increase as moisture content decreases for corn grits (Anderson et al., 1969; Conway, 1971), corn starch (Mercier and Feillet, 1975; Gomez and Aguilera, 1984), wheat starch (Paton and Spratt, 1984), and wheat, rye, barley and oat flour (Vainionpaa, 1991).

Variations in WAI and WSI may be interpreted based on starch-water interactions that govern the solid-phase structure of the processed starch. Solubility may be related to the lower molecular weight of starch components while a low WAI reflects the restricted water accessibility of extruded starches ascribed to a compact structure (Colonna et al., 1989).

2.2 Response Surface Methodology

The extrusion cooking process of biological materials is very complex because of the many interdependent variables involved. However, valuable information on effects to be expected from changes in processing variables may be obtained from relatively simple models based on response surface methodology (RSM), first introduced by Box & Wilson (1951). Ample literature is available on the principles and applications of the methodology (for example, Box and Hunter, 1957; Cochran and Cox, 1957; Davies, 1963; Myers, 1971, Murphy, 1977, Box and Draper, 1987). RSM is a mathematical and statistical method based on regression analysis on quantitative data from appropriate experimental designs to construct and solve multivariate equations describing the relationship of the dependent variables to product quality characteristics and to process and design parameters (Olkku et al., 1983). RSM was designed to reduce the number of experiments while still obtaining the maximum information from them. The results are presented by response surface mapping to describe graphically the relation of one property versus two process parameters. According to Rose (1981), RSM has been especially useful in the study of processes or phenomena involving many variables and when reaction kinetics and/or underlying mechanisms are incompletely known.

2.2.1 Basic Concepts and Assumptions of RSM

RSM is based on the assumption that when k factors (independent variables) are being studied in an experiment, the response (dependent variable) will be a function of the levels at which these factors are combined (x_k). Thus,

$$\eta = f(x_1, x_2, \ldots., x_k) \tag{11}$$

where η is the response, and the form of the function f is unknown, and perhaps extremely complicated. However, RSM approximates f by a low order polynomial in some region of the independent variables. x's are the coded variables. The reason for coding the levels of the independent variables is to have homogeneous scales on the axes to generate a spherical symmetry which makes the subsequent study of the response surface much easier.

For the case the approximating function is linear in the variables, the response is written in terms of the design variables, as first order model:

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \quad (12)$$

In the above expression, the ß's are coefficients or empirical parameters which have to be estimated from the data. The first order model is often used in studying f in narrow regions of the independent variables, for example when making a rough survey of a target area in optimization.

The second order approximating functions have been most frequently applied in the food field, and can be generally expressed as:

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq i}^{k} \beta_{ij} x_i x_j + E \quad (13)$$

Where η is the response variable, x_i and x_j are independent variable, k is the number of independent variables, and E is the random error. The rationale for polynomial approximation of *f* is based on the Taylor series expansion of *f* around the point $x_1 = x_2 = x_3 = \ldots = x_k = 0$.

The fundamental assumptions on which RSM is based are summarized as follows:

1. A structure or model $\eta = f(x_1, x_2, \ldots, x_k)$ exists and is either very complicated or unknown. The variables involved are quantitative and continuous.
2. The function *f* can be approximated in the region of interest by a low-order polynomial such as Equation 11 or 12.

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3. The independent variables $x_1, x_2, \ldots, x_k$ are controlled in the observational process and measured with negligible error.

Selection of the appropriate independent variables and the choice of their actual levels is of utmost important. The levels of the coded variables, used in computing the response surface models are defined by:

$$x_i = \frac{X_i - X_c}{\Delta X_i} \tag{14}$$

where x_i is the coded value of the variable X_i, X_i is the real or natural value of the variable, X_c is the real value of the experimental center point of X_i and ΔX_i is the unit change of X_i.

Regarding the order in which the runs are performed, it is advisable to run experiments in random order under steady conditions if a random sequence of the runs does not raise any operating trouble. However, it is probably best to follow an order which minimizes the troubles which might be sources of error. When all responses for a dependent variable η have been obtained the next step is to find the constant ß for the response surface equation. This is usually done by regression analysis.

2.2.2 The Applications of RSM in Food Processing

Response Surface Methodology techniques have been successfully applied in many areas such as agronomy, biology, chemistry, engineering, food industry, textiles, and others. In 1951, Box and Wilson described a scientific approach to determining optimum conditions which combined special experimental designs with Taylor first and second order equations in a sequential testing procedure called "Path of Steepest Ascent." Underwood (1962) applied RSM in designing extrusion screws. The dependent variables in his experiment were rate of extrusion, melt temperature, net power required, smoothness of operation, and thoroughness of mixing whereas the length of the metering section, channel depth in the metering section, the channel depth in the feed section and the screw speed were considered as independent variables.

In the complicated field of food extrusion RSM was used successfully in the extrusion of cooking of corn starch (Lawton et al., 1972), triticale (Lorenz et al., 1974), cottonseed meal (Taranto et al., 1975), soybean (Aguilera and Kosikowski, 1976; Maurice and Stanley, 1978), starch-protein-sugar pastes (Olkku and Vainionpaa, 1980), barley starch (Linko et al., 1980b), fish and soy mixtures (Murray et al., 1980). Olkku et al. (1983) employed RSM in the steady-state modeling of extrusion cooking. RSM has been further applied to analyze the extrusion cooking of wheat based materials (Olkku and Vainionpaa, 1980; Meuser et al., 1982; Paton and Spratt, 1984; Vainionpaa et al., 1984; Linko et al., 1985; Vainiopaa and Malkki, 1987; Vainiopaa, 1989; and Vainiopaa et al., 1989), rice (Vainiopaa, 1992), and rice and chick pea blends (Bhattacharya and Prakash, 1994).

Halek and Chang (1991) employed RSM to study extrusion processing of cornmeal in a co-rotating twin-screw extruder. In their experiment three-variable, three-level RSM: feed moisture content (20, 25 and 30%), barrel temperature (100, 150 and 200°C), and screw speed (100, 200 and 300 rpm) was investigated. From its many applications it can be concluded that RSM has been proved to be a powerful tool in providing solutions of a large variety of problems such as optimization of complex products and process variables in food processing.

2.3 Factorial Design

This design is characterized by the fact that the effect of changing one variable can be assessed independently of the others. It is accomplished by using each of the possible combinations of the levels of each factor. The advantages of this design over the one-factor-at-a-time experimental technique are that it lends itself to assessing the interaction among factors, and it is more precise in terms of the effect of a factor used. A factorial experiment with k factors each at three levels is referred to as 3^k factorial. The class of 3^k factorial experimental designs can be useful when the regression model is best represented by a second order polynomial (Dey, 1985).

2.3.1 Fractional Factorial Design

It is a design consisting of a fraction of a complete factorial experiment. The concept of this design was introduced by Finney (1945). Consider a Taylor's series expansion:

$$\eta = \eta_0 + \sum_{i=1}^{k} \left[\frac{\partial \eta}{\partial x_i}\right]_0 x_i + \frac{1}{2}\sum_{i=1}^{k}\sum_{j=1}^{k}\left[\frac{\partial^2 \eta}{\partial x_i \partial x_j}\right]_0 x_i x_j + \dots \qquad (15)$$

Where η is a function of k coded independent variables, x_1, x_2, ... x_k, coded so that the center of the region of interest is at the origin. If we truncate terms of order higher than the second degree, the expression yields the second degree approximation, thus

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq i}^{k} \beta_{ij} x_i x_j \qquad (16)$$

For a complete understanding of this design the reader is referred to Davies (1956) or other books on experimental design (for example, Dey, 1985). Fractional factorial are useful in the following areas:

1. Situations where some of the high order interactions can be tentatively assumed to be zero;
2. In screening from a large set of factors, some factors with large effects;
3. In a sequential program of experiments;
4. When the amount of experimentation required by the complete factorial is more than the experimenter can afford.

As mentioned above, while using a fractional factorial design, an assumption regarding the absence of certain higher order interactions has to be made in order to obtain unbiased estimates of lower order effects. This, however, should not be taken as a drawback of the design since fractional factorial design has been used effectively in many areas such as: agriculture, chemistry, genetic improvement, food processing, and others. In situations where the absence of higher order interactions (for example, 3-factor and higher) can be validly assumed, fractional factorials provide useful information on lower order effects at a considerable saving (Dey, 1985).

CHAPTER III

MATERIALS AND METHODS

The general plan of this experiment was to use a fractional- factorial experimental design with three independent variables (feed moisture, barrel temperature and screw speed). The resulting dependent variables were then recorded and used in calculating the specific mechanical energy of the system. The details of the overall experimental set up, data collection and analysis processes are presented as detail as possible.

Raw material: Teff flour obtained from Workinesh Spice Blends, Inc. of Oshtemo, Michigan was used as a feed material for all extrusion conditions. The compositions of the teff flour are shown in Table 3.1. The water used was tap water. After the extrusion cooking process, the collected teff extrudate products were dried for 20 hours at 60±2°C in a forced-draft oven and sealed in plastic bags after cooling so as to obtain a relatively uniform moisture in the samples. The final moisture content of the cylinderical rods (extrudates) was 3-4%.

Table 3.1 Compositions of Teff Flour

Component	Average compositions[a]	Dry Basis Compositions
Moisture content	12 %	
Dry Matter	88 %	
Crude Protein	13.59 %	15.44 %
Crude Fat	0.62 %	0.70 %
Acid Detergent Fiber	9.30 %	10.60 %
Ash	3.41 %	3.87 %
Sulfur	0.20 %	0.23 %
Phosphorus	0.48 %	0.54 %
Potassium	0.35 %	0.40 %
Magnesium	0.18 %	0.20 %
Calcium	0.22 %	0.25 %
Sodium	0.01 %	0.01 %
Iron	298 ppm	339 ppm
Aluminum	275 ppm	313 ppm
Manganese	67 ppm	76 ppm
Zinc	36 ppm	41 ppm
Copper	8 ppm	9 ppm
Boron	1 ppm	1 ppm

[a] Teff flour analysis as reported by A&L Great Lakes Laboratories, Inc., Fort Wayne, Indiana.

3.1 Extruder

A Werner & Pfleiderer, model ZSK-30, co-rotating twin-screw extruder (Werner & Pfleiderer Corp., Ramsey, NJ) was used (Figure 3.1) to extrude the teff flour. The two screws are intermeshing with a self-wiping profile. The extruder barrel has five individually controlled temperature zones. The barrel cooling system consists of a supply line with solenoid valves and a return line with check valves to regulate flow and temperature in each zone. The temperature is monitored by steel thermocouples in the barrel sections and controlled by the temperature controllers in the electrical panel. Water was used as the cooling medium. The barrel length-to-diameter ratio (L/D) of the extruder was 32.5. A food die head and holder with two circular die holes of each 2 mm in diameter (Figure 3.2) was hinged to the extruder in such a way that the die holes were aligned with the screw tips. The die head was cleaned, closed and tightened to the end of the extruder barrel before each run. The screw configuration used is shown in Table 3.2. Actual photograph of the screw profile used for this experiment is also shown in Figure 3.3.

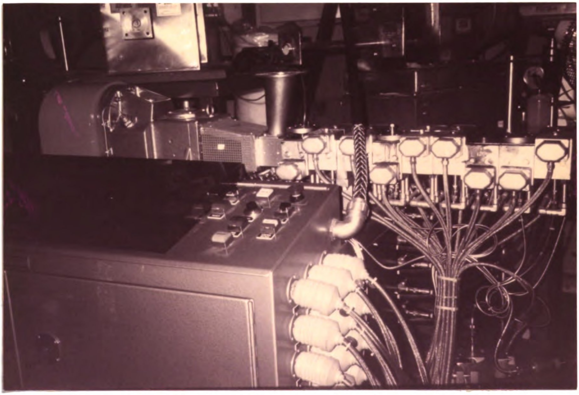

Figure 3.1 ZSK-30 Twin-Screw Extruder

Table 3.2. Extruder Screw Configuration used in Teff Extrusion

Screw element type X/Z[a], KB/A°/Y/Z[b]	Number of screw elements
S/10[c]	1
20/10	1
42/42	10
28/28	6
28/14	1
20/20	2
20/10	1
20/20	3
KB/45°/5/14	2
20/20	1
KB/45°/5/14	1
20/20	1
KB/45°/5/14	2
KB/45°/5/14 LH	1
20/10	1
20/20	1
20/10	1
20/20	4

[a]X = distance in mm to make one complete revolution, Z = length of screw element (mm).
[b]KB = kneading block, A° = angle of flight, Y = number of disks, and Z = length of screw element (mm).
[c]S indicates the starting element

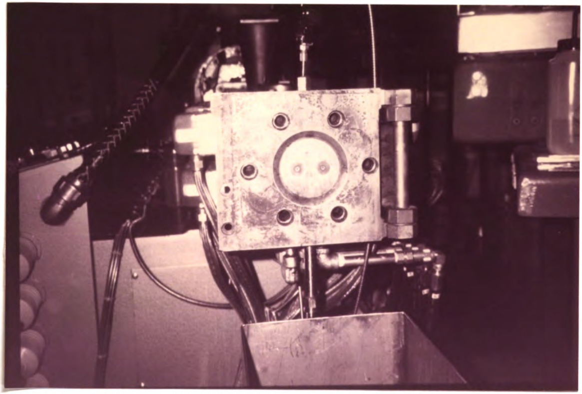

Figure 3.2 Food Die used in Teff Extrusion

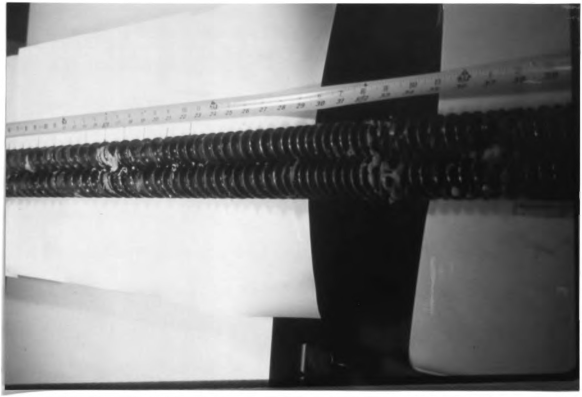

Figure 3.3 Screw Profile used in Teff Extrusion

3.2 Extrusion Conditions

The teff flour was fed into the extruder by weight-loss differential weigh feeder with acri-lok (Acrison, Inc., Moonachie, New Jersey). Tap water at ambient temperature was added to the flour inside the extruder via an inlet port in the top of the barrel, 8.2 cm downstream from the center of the flour feed port, using a variable speed drive pump with speed controller (Cole-Parmer Instrument Co, Chicago, Illinois). The pump was calibrated to give a total moisture content of feed material as 20, 25 and 30%. The dry feed rate was kept constant at 9.07 kg/h (20 lb/h). During the preliminary runs, a dry feed rate of 4.54 kg/h (10 lb/h) was used. However, this low dry feed rate combined with higher barrel temperature, resulted in instabilities such as clogging of the teff extrusion process. The ranges of independent variables were chosen so as to represent practical and stable operation of the extruder.

All barrel and product temperatures, percent torque, screw speed, die pressure, and feed rate shown in the control panel were recorded at five regular time intervals. Steady-state extrusion conditions were assumed to have been reached when there were no visible drifts in product temperatures and percent torque for at least 5 min. Samples were then collected in zipper plastic bags, sealed and stored at room temperature (≈ 25°C) for further analyses. Specific Mechanical Energy (SME) input was calculated using the following formula (Hsieh et al., 1990b):

$$SME = \frac{rpm(run)}{rpm(rated)} X \frac{\%Torque(run)}{100} X \frac{kW(rated)}{Feed\ rate} \qquad (17)$$

3.3 Functional Testing of Extrudates

3.3.1 Product Moisture Content

Wet basis moisture contents of the extrudates were determined as the weight loss of triplicate samples of extrudates after drying in an oven for 1 h at 130°C (AOAC, 1990).

3.3.2 Expansion Ratio

The expansion ratio was measured as the ratio of the diameters of teff extrudates to that of the die. The diameters of the samples were measured with a digital caliper accurate to 0.01 mm. Fifteen replicates were made to obtain the average.

3.3.3 Bulk Density

The bulk density was determined by weighing pieces of cylindrical extrudates and measuring their length and average diameter. This method of measuring bulk density was also used by other workers in the field of extrusion (Gujska and Khan, 1991). The number of replications was five.

These data were used to calculate the density as follows:

$$Density = \frac{piece\ weight}{apparent\ piece\ volume}\ ,where \qquad (18)$$

$$\text{Apparent volume} = \frac{\pi(\text{diameter})^2}{4} \times \text{length} \tag{19}$$

3.3.4 Water Absorption Index (WAI) and Water Solubility Index (WSI)

WAI and WSI were determined as described by Anderson et al. (1969). A 2.5 g sample of ground product (60 mesh) was suspended in 30 ml of water (pH 6-7) at room temperature, stirred intermittently over a 30 minute period, and centrifuged at 1000 X g for 15 minutes (Sorvall RC-5B refrigerated superspeed centrifuge, Dupot Company, Newtown, CT). The gel pellet was weighed and WAI was calculated as gram gel/gram dry sample. The supernatant was evaporated on aluminum dish in air oven and WSI calculated as percentage dry solid/2.5 g sample.

3.3.5 Color

The color of raw teff flour and ground extrudates was measured in a Hunter Lab D 25L Colorimeter (Hunter Associates Lab, Inc., Reston, VA). L (lightness), a (redness), and b (yellowness) values are reported. Color readings were taken after the sample was placed into a 100 mm dish. The dish was then rotated 90 degrees and readings were taken again. The average of the two readings of the same sample was reported for each sample. Duplicate samples were used for each experimental run. Similar procedure of color determination was used for rice flour by Grenus et al. (1993); beans (Gujska and

Khan, 1991) and Fletcher et al. (1985) for maize grits.

3.4 Experimental Design and Statistical Analysis

Changing one extrusion variable while keeping others constant gives no insight into the interactions among the process variables unless many combinations are examined (Colonna et al., 1989). Employing a statistically designed multiple-factor experiment for economy of experimental points together with response surface methodology has been used as a solution to overcome this problem.

A fractional factorial experimental design with three variable, three-level response surface methodology with three replicates at the center point (Henika, 1972) was used. The three major extrusion variables investigated were total feed moisture (20-30%), barrel temperature in the last two heating zones (125-175°C), and screw speed (100-300 rpm). The actual experimental conditions are shown in Table 3.3. The decision for the levels of the independent variables was based on the preliminary extrusion runs and observations made by the author and his major Professor. Two replications were made for each run.

Data obtained were analyzed by the response surface regression (RSReg) procedure in MINITAB (Release 10.1, Minitab Inc. State College, PA). The actual extrusion process conditions were coded to the levels (x) of -1, 0 and +1 according to the following equations:

$$x_1 = \frac{MC - 25}{5} \qquad (20)$$

$$x_2 = \frac{T - 150}{25} \tag{21}$$

$$x_3 = \frac{N - 200}{100} \tag{22}$$

Where x_1 is the dimensionless moisture content, MC the moisture content (%wet basis); x_2 is the dimensionless barrel temperature, T the actual barrel temperature (°C); and x_3 is the dimensionless screw speed, N the actual screw speed (rpm).

The second-order polynomial equation for the response function (η) against three independent variables (x_1 = moisture content, x_2 = barrel temperature, and x_3 = screw speed) in coded terms can be represented as:

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 \tag{25}$$

The response surface regression procedure estimates parameters of a complete quadratic response surface by least-squares regression and gives information about the fit in the form of analysis of variance (ANOVA). From the ANOVA, the contribution of linear, quadratic and cross product effects to the statistical fit was obtained. An IBM-compatible Personal Computer was used to perform the statistical calculations and all the analyses.

Table 3.3 Experimental Design for Teff Extrusion

Test run	Moisture content (%)	Screw speed (rpm)	Barrel temperature profile (°C)				
			zone 1	zone 2	zone 3	zone 4	zone 5
1	30	200	30	50	75	175	175
2	25	100	30	50	75	175	175
3	25	300	30	50	75	175	175
4	20	200	30	50	75	175	175
5	25	200	30	50	75	150	150
6	30	200	30	50	75	125	125
7	25	300	30	50	75	125	125
8	25	100	30	50	75	125	125
9	20	200	30	50	75	125	125
10	25	200	30	50	75	150	150
11	30	100	30	50	75	150	150
12	30	300	30	50	75	150	150
13	25	200	30	50	75	150	150
14	20	100	30	50	75	150	150
15	20	300	30	50	75	150	150

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Model Fitting

The experimental data and response surface layout are shown in Appendix A. After the raw data were analyzed by the response surface regression procedure, a stepwise regression procedure was used to select the "best" model equation under the specified conditions for each dependent variable. Stepwise regression procedure inserts the variables in turn until the regression equation is satisfactory using the partial correlation coefficient as a measure of the importance of variables not yet in the equation. It is also one of the best of the variable selection procedures recommended its use. Computer printout of the stepwise regression procedure is given in Appendix B. Coded or "standardized" x_i, values were used to provide proper preference among the variables in the calculation of the models.

To assess the significance of each effect (linear, quadratic and cross product), the parameter estimates, t-ratios, R-square (the percentage square of the multiple correlation coefficient), and P values obtained from the regression outputs were considered. F-to-enter and F-to-remove value of 4 was used for the stepwise regression procedure. The non-significant terms, judged by the tests ($P < 0.05$) from the second order polynomial were deleted and the equation was recalculated to give the final model for each dependent variable. Sensible examination of the model through examination of residuals was also made.

All the models discussed in this work are statistically significant at the 5% level. Models for water absorption index, product moisture content, %Torque, die temperature, and die pressure, however, show considerable lack of fit. For such models with significant lack of fit, the nature of inadequacy was sought by analyzing the residuals. The lack of fit shows that there is variation in the model other than random error (such as cubic effects of the independent variables). However, models with a correlation coefficient as high as 90% or more can give an adequate overall view over the multifactorial field of extrusion cooking (Vaniopaa, 1991). Besides, the residual analyses showed that these deficient models can still be used with proper caution.

4.2 Expansion Ratio

In the teff extrusion experiments, the expansion ratio (ER) of the dry extrudate rods were between 2.37 and 2.99. From the raw data, the lowest ER value was obtained with a feed moisture content of 30 %, barrel temperature of 150°C and at a screw speed of 100 rpm, whereas the highest ER value was with 20 %, 150°C, and 100 rpm, respectively. This observation indicated that ER was significantly affected by feed moisture only among the three independent variables considered.

Table 4.1 shows the estimated regression coefficients, t-ratios and P values for ER.

The t-ratio is a statistic that tests the null hypothesis that the model parameter is zero. The P value is the probability of getting a greater t-ratio, its value being less than 0.05 is often considered as significant evidence that the parameter is not zero. Based on the P values, it was found that among the linear and second order effects, only that of moisture was significant ($P<0.05$). The results also indicated that all of the interaction terms were significant ($P<0.05$).

Table 4.1. Estimated Regression Coefficients for Expansion Ratio Using Coded Variables (x1 = feed moisture, x2 = barrel temperature and x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	2.6977	0.02300	117.278	0.000
x1	-0.1792	0.01409	-12.721	0.000
x2	-0.0169	0.01409	-1.197	0.245
x3	-0.0068	0.01409	-0.479	0.637
x1*x1	-0.0842	0.02073	-4.062	0.001
x2*x2	0.0259	0.02073	1.247	0.227
x3*x3	0.0348	0.02073	1.679	0.109
x1*x2	0.0809	0.01992	4.060	0.001
x1*x3	0.0627	0.01992	3.146	0.005
x2*x3	0.0830	0.01992	4.167	0.000

s = 0.05634 R-sq = 92.0% R-sq(adj) = 88.4%

The resulting second order polynomial using coded variables, after removing the non-significant terms and recalculating becomes:

$$ER = 2.732 - 0.179x_1 - 0.089x_1^2 + 0.081x_1x_2 + 0.063x_1x_3 + 0.083x_2x_3 \quad (24)$$

The final model equation was obtained from the stepwise regression output (Appendix B). Equation 24 accounted for 89.69 % of the total variation in ER and from which 64.8 % of this variability was accounted by moisture content with in the extrusion processing variables considered in the experiment.

Figure 4.1 shows the response surface for ER against feed moisture and barrel temperature. Eventhough the effect of temperature on ER was not significant, it had greater effect than that of screw speed as evidenced by comparing coefficients of x_1 and x_3.

It should be noted that due to the unavailability of published data on expansion ratio of teff, it was not possible to directly compare this work with the others. However, attempts are made to compare it with other cereals. Even in this case the differences in product compositions and extrusion conditions used by other researchers made it still difficult to compare results. Nevertheless, such general comparisons should give general idea how teff behaved in extrusion cooking process compared to other cereals with in the range of variables.

Increasing feed moisture content of teff flour caused a decrease in ER. The highest ER was obtained at 20 % moisture and decreased significantly as moisture content increased up to 30 %. Similar results were described by Faubion and Hoseney (1982a) for wheat starch, and by Chinaswamy and Hanna (1988) and Owusu-Ansah et al. (1984) for corn starch. This was commonly observed in many snack foods (Harper, 1981) which may be because the amount of expansion occurring in food material depends on the pressure differential between the die and atmosphere. Foods with lower moisture tend to be more viscous than those with higher moisture and, therefore, the pressure differential would be smaller for higher moisture foods leading to a less puffed product. Chinnaswamy and Hanna (1988) described that low moisture content in starch may restrict flow of material inside the extruder barrel, increasing shear rate and residence time, which might increase the degree of starch gelatinization and expansion.

Diameteral expansion of starch materials is known to depend on elasticity of the melt (Launay and Lisch, 1983) and a decrease in moisture content results in improved moisture distribution and gives a higher melt elasticity that will increase ER. This may also explain why the effect of barrel temperature was not significant on ER since melt elasticity is not strongly dependent on temperature (Launay and Lisch, 1983). According to Figure 4.1 higher temperatures at higher feed moisture content resulted in a slight increase in ER. This may be because at higher moisture the higher temperature produced higher vapor pressure to favor expansion. However, at low moisture content higher temperature resulted in a decrease in ER, and the maximum ER was obtained at the lowest temperature considered in the experiment. A possible explanation for such phenomenon could be higher barrel temperature especially at low moisture content decreases melt viscosity to reduce expansion. Similar results were reported for degerminated corn meal extruded at 20-30 % moisture at 100-200°C (Halek and Chang,

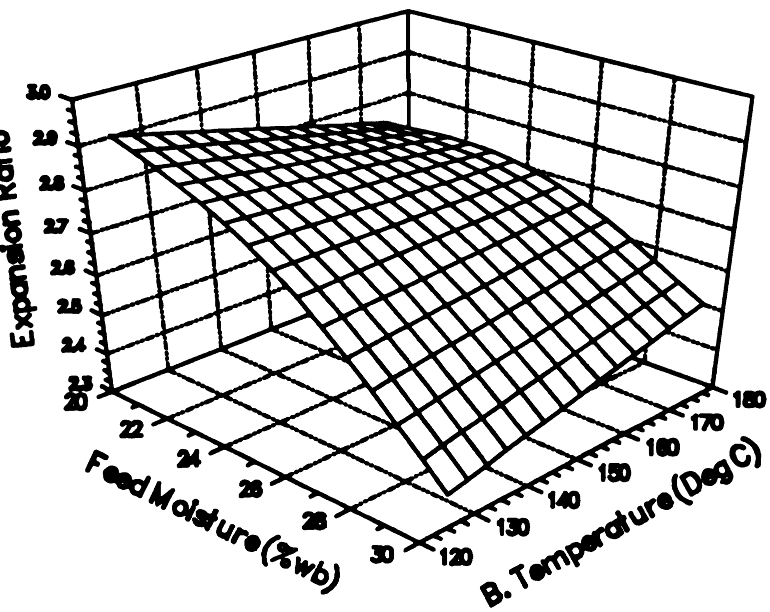

Figure 4.1 Expansion Ratio versus Feed Moisture and Barrel Temperature at 200 rpm Screw Speed

1991). Another explanation for the lower radial expansion at high temperature could be the decreased die pressure exerted by the dough at higher temperature.

The composition of the raw materials has a significant effect on the texture, color, and taste of the extruded product. Mercier and Feillet (1975) reported that among different types of starches, only a few expanded better than others. Apparently, starch content and quality factors (amylose, amylopectin) most significantly affected expansion properties (Chinnaswamy and Hanna, 1988). The maximum expansion obtained was 291 %. In general, this value was higher than the expansion ratio values reported for wheat flour extruded at 14% moisture and 135°C barrel temperature (Mannonen, 1979); barley flour extruded at 18% moisture and 160°C barrel temperature, and oat flour extruded at 16% moisture and 135°C temperature (Hagqvist, 1981).

According to Horn (1977), the maximum expansion obtained with whole grains was 400% (starch content in raw materials was 65-78%). The lower ER of teff extrudates could be because of the lower content of starch in the raw material. Because starch has been known to play an important role as the major component that builds a matrix of extrudate and a key element responsible for expansion. In earlier studies, radial expansion decreased with increasing fiber content (Anderson et al., 1981; Breen et al., 1977; Lawton et al., 1985; Lue et al., 1991). Therefore, when examining the ER of teff extrudates, the fiber content of teff flour needs consideration. Teff flour used in the experiment had relatively higher fiber content (9.3%) as compared to wheat flour (1-2%); corn flour (0.5-0.7%); rice flour (0.3-0.35%), and oat flour (2-12%).

4.3 Bulk Density

The Bulk Density (BD) of the dry extruded rods varied from 0.126 to 0.316 g/cm^3. Table 4.2 shows the regression coefficients for BD. Figure 4.2 shows the response surface for BD as a function of feed moisture content barrel temperature. These two independent variables jointly accounted for 75.89% of the total variation in BD. All the linear terms, square terms and one of the interactions (moisture * temperature) were significant ($P<0.05$).

Table 4.2 Estimated Regression Coefficients for Bulk Density Using Coded Variables (x1 = feed moisture, x2 = barrel temperature and x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	0.19405	0.003015	64.362	0.000
x1	0.05601	0.001846	30.337	0.000
x2	-0.03373	0.001846	-18.270	0.000
x3	-0.03132	0.001846	-16.963	0.000
x1*x1	0.02000	0.002718	7.360	0.000
x2*x2	-0.00647	0.002718	-2.382	0.027
x3*x3	0.00765	0.002718	2.813	0.011
x1*x2	-0.01075	0.002611	-4.116	0.001
x1*x3	-0.00538	0.002611	-2.059	0.053
x2*x3	-0.00185	0.002611	-0.707	0.488

s = 0.007385   R-sq = 98.8%   R-sq(adj) = 98.2%

Barrel temperature and screw speed had a negative effect on BD. As could be expected moisture had the highest effect followed by temperature and screw speed. The resulting polynomial using coded variables after removal of non-significant terms on recalculation gives:

$$BD = 0.194 + 0.056x_1 - 0.034x_2 - 0.031x_3 + 0.02x_1^2 - 0.007x_2^2 + 0.008x_3^2 - 0.011x_1x_2 \quad (25)$$

The less dense product result obtained with an increase in expansion ratio was in agreement with the results of Harmann and Harper (1973); Anderson et al., (1969); Launay and Lisch (1983), and Fletcher et al., (1985) for extrusion cooked corn grits. BD decreased with screw speed. One possible explanation given (Hoseney et al., 1991) was that air was trapped in the melt because of the action of the screws. At higher screw speed, more air bubbles were trapped which resulted in less dense teff extrudate

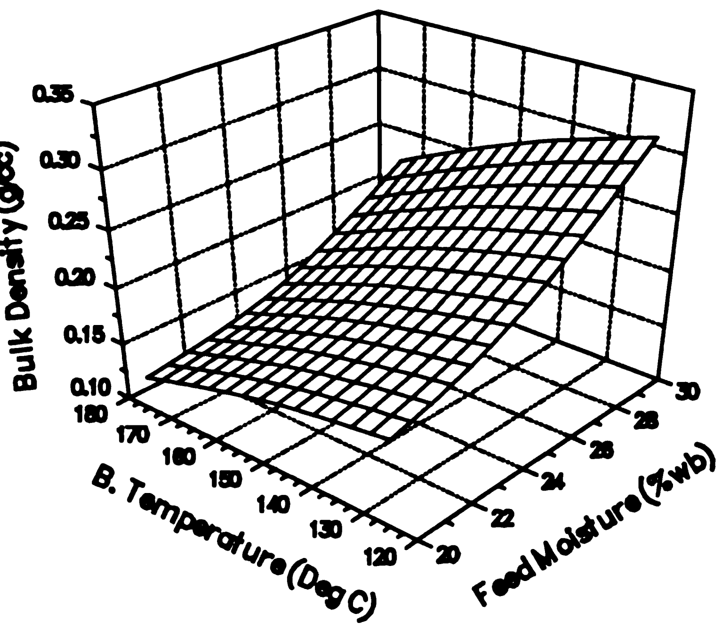

Figure 4.2 Bulk Density versus Feed Moisture and Barrel Temperature at 200 rpm Screw Speed

4.4 Water Absorption Index

The Water Absorption Index (WAI) of ground extruded samples varied from 4.869 to 6.815 g/g. This range of WAI values obtained in this experiment are in agreement with the range of 3-10 g/g values reported for extruded starches (Anderson et al., 1969; Conway, 1971; Mercier and Feillet, 1975; Gomez and Augilera, 1984). In general, the WAI values obtained for teff flour are higher than the values reported for wheat flour (Mannonen, 1979), barley flour and oat flour (Hagqvist, 1981). Table 4.3 shows the regression coefficients for WAI. Figure 4.3 shows the response surface for WAI as a function of barrel temperature and screw speed. These two variables accounted for 46.68% of the total variation in WAI.

Table 4.3. Estimated Regression Coefficients for Water Absorption Index Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	6.0624	0.11490	52.761	0.000
x1	0.2635	0.07036	3.745	0.001
x2	0.3354	0.07036	4.767	0.000
x3	-0.3467	0.07036	-4.927	0.000
x1*x1	-0.0084	0.10357	-0.082	0.936
x2*x2	-0.3436	0.10357	-3.318	0.003
x3*x3	0.0453	0.10357	0.438	0.666
x1*x2	-0.0580	0.09951	-0.583	0.567
x1*x3	0.0060	0.09951	0.060	0.953
x2*x3	0.2780	0.09951	2.794	0.011

s = 0.2815 R-sq = 80.1% R-sq(adj) = 71.2%

All the linear terms, one of the square terms (temperature * temperature) and one of the interaction terms (temperature * screw speed) were significant ($P<0.05$).The resulting polynomial, after removal of non-significant terms and on recalculation gives:

$$WAI = 6.083 + 0.264x_1 + 0.335x_2 - 0.347x_3 - 0.346x_2^2 + 0.278x_2x_3 \quad (26)$$

WAI increased with moisture and temperature. This direction of influence of process conditions on WAI of extruded teff flour is consistent with the findings of Owusu-Ansah et al. (1982) on corn starch and Olkku and Hagqvist (1983) on barley extruded with twin-screw extruder.

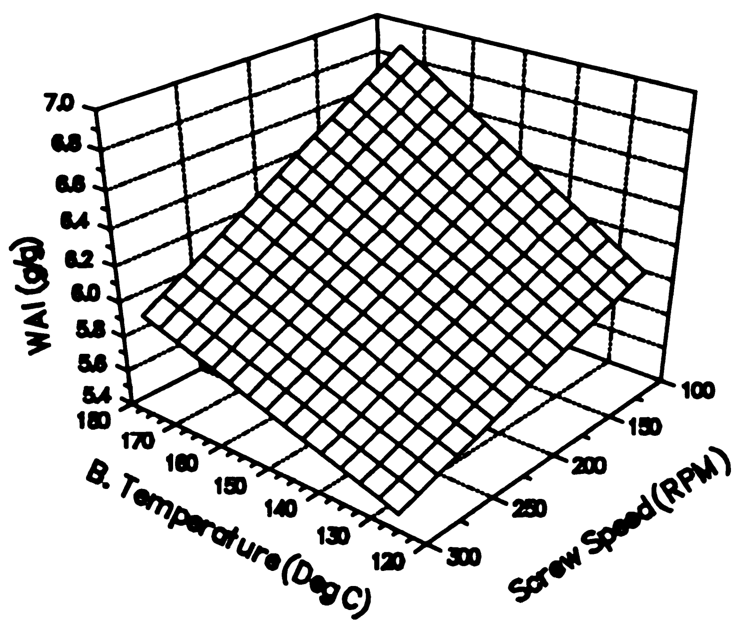

Figure 4.3 Water Absorption Index versus Barrel Temperature and Screw Speed at 25% Feed Moisture

4.5 Water Solubility Index

The water solubility index (WSI) of the ground extruded samples varied from 4.523 to 17.031%. Table 4.4 shows the regression coefficients for WSI. The effect of feed moisture and barrel temperature on WSI is presented in Figure 4.4. These two variables accounted for 55.58% of the variability in WSI. All the linear, square and interaction terms were significant ($P < 0.05$). When forming the final polynomial equation, however, the square term for screw speed (x3 * x3) and the interaction term for moisture and temperature were omitted based on the results of the stepwise regression. The resulting polynomial after recalculation gives:

$$WSI = 6.526 - 2.75x_1 + 3.33x_2 + 2.69x_3 + 1.84x_1^2 + 2.55x_2^2 - 1.66x_1x_3 + 0.91x_2x_3 \quad (27)$$

Higher WSI values were obtained at low moisture and high temperature where the process conditions are the most severe. The increase in WSI as moisture decreases is in agreement with earlier works for corn grits (Anderson et al., 1969; Conway, 1971); corn starch (Mercier and Feillet, 1975) and wheat starch (Paton and Spratt, 1984). Greater shear degradation of starch during low moisture extrusion was given as the main reason for such result (Anderson et al., 1969). Dextrinization as a predominant mechanism of starch degradation during low-moisture, high-shear extrusion was also noted by Gomez and Augilera (1984).

Table 4.4 Estimated Regression Coefficients for Water Solubility Index Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	p
Constant	5.945	0.3428	17.345	0.000
x1	-2.748	0.2099	-13.092	0.000
x2	3.327	0.2099	15.849	0.000
x3	2.685	0.2099	12.793	0.000
x1*x1	1.917	0.3090	6.204	0.000
x2*x2	2.622	0.3090	8.485	0.000
x3*x3	0.944	0.3090	3.055	0.006
x1*x2	-0.760	0.2968	-2.559	0.019
x1*x3	-1.656	0.2968	-5.578	0.000
x2*x3	0.911	0.2968	3.068	0.006

s = 0.8396 R-sq = 97.4% R-sq(adj) = 96.2%

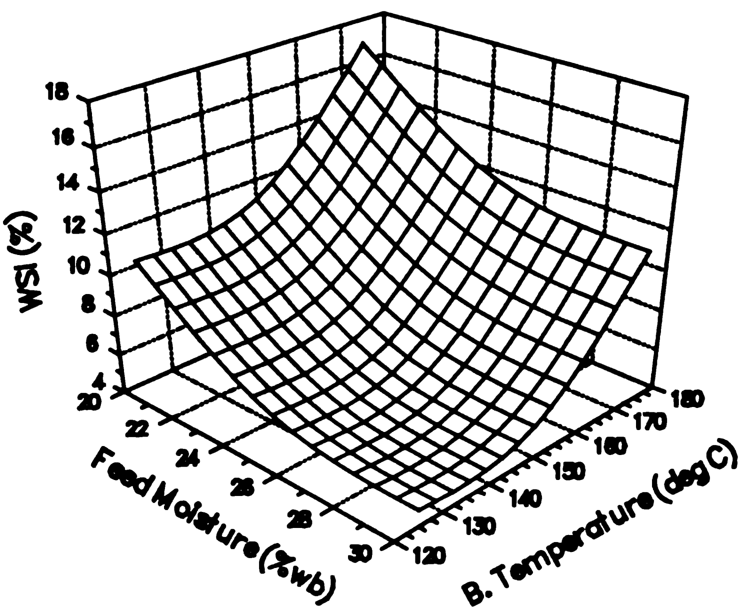

Figure 4.4 Water Solubility Index versus Feed Moisture and Barrel temperature at 200 rpm Screw Speed

4.6 Product Moisture Content

The wet basis product moisture content (PMC) of the extrudates varied from 5.14 to 14.08%. Table 4.5 shows the regression coefficients for PMC. All the linear terms, one of the interactions (moisture * temperature) and two of the square terms except (temperature * temperature) were significant ($P < 0.05$).

Table 4.5 Estimated Regression Coefficients for Product Moisture Content Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	p
Constant	8.6024	0.12051	71.381	0.000
x1	3.2358	0.07380	43.846	0.000
x2	-0.8087	0.07380	-10.958	0.000
x3	-0.7656	0.07380	-10.374	0.000
x1*x1	0.8455	0.10863	7.783	0.000
x2*x2	-0.0603	0.10863	-0.555	0.585
x3*x3	0.6295	0.10863	5.795	0.000
x1*x2	-0.3548	0.10437	-3.400	0.003
x1*x3	0.0060	0.10437	0.058	0.955
x2*x3	0.1889	0.10437	1.810	0.085

s = 0.2952 R-sq = 99.1% R-sq(adj) = 98.7%

Higher feed moisture and lower extrusion temperature produced extrudates with higher moisture content (Figure 4.5), as could be expected.

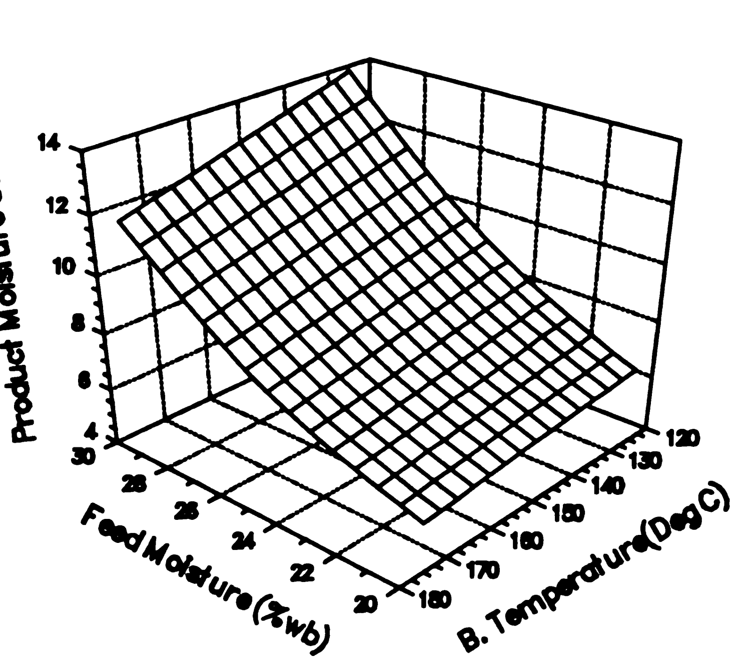

Figure 4.5 Product Moisture Content versus Feed Moisture and Barrel Temperature at 200 rpm Screw Speed

The resulting polynomial after removal of non-significant terms on recalculation gives:

$$PMC = 8.565 + 3.236x_1 - 0.809x_2 - 0.766x_3 + 0.85x_1^2 + 0.63x_3^2 - 0.35x_1x_2 \quad (28)$$

Similar trends were observed for rice flour using a Clextral BC 45 twin-screw extruder by Sun Pan et al. (1991) and for corn meal flour using a ZSK-30 twin-screw extruder by Halek and Chang (1991).

4.7 Torque

The percentage torque (%T) developed during teff extrusion varied from 24.24 to 60.29 %. The regression coefficients and response surface for %T are shown in Table 4.6 and Figure 4.6, respectively. All the linear terms and two of the square terms except (moisture * moisture) and two of the interactions except (moisture * temperature) were significant ($P < 0.05$).

The resulting polynomial after removal of non-significant terms which accounts for 97.5% of the total variation in torque, on recalculation gives:

$$\%T = 32.83 - 5.68x_1 - 8.08x_2 - 6.34x_3 + 2.4x_2^2 + 4.69x_3^2 + 2.89x_1x_3 + 4.23x_2x_3 \quad (29)$$

Table 4.6 Estimated Regression Coefficients for Percentage Torque Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	32.825	0.7496	43.792	0.000
x1	-5.678	0.4590	-12.370	0.000
x2	-8.083	0.4590	-17.610	0.000
x3	-6.339	0.4590	-13.811	0.000
x1*x1	0.008	0.6757	0.012	0.991
x2*x2	2.402	0.6757	3.555	0.002
x3*x3	4.688	0.6757	6.939	0.000
x1*x2	0.152	0.6491	0.234	0.818
x1*x3	2.886	0.6491	4.446	0.000
x2*x3	4.231	0.6491	6.517	0.000

s = 1.836 R-sq = 97.5% R-sq(adj) = 96.3%

A minimum torque value can be obtained by employing higher moisture, barrel temperature and screw speed. The lower torque at higher screw speed could be explained by the length of filled flights in the extruder barrel (Ollet et al., 1989). In this experiment, the dry feed rate was fixed at 9.07 kg/h and the extruder was starve-fed. An increase in the screw speed would cause a decrease in the length of filled section (Tayeb et al., 1989) and thus the torque was reduced. The shorter the filled length in the barrel, the smaller the load of the extruder motor drive and hence the lower the extruder torque at higher screw speed. Similar results were reported by Guy and Horne (1988).

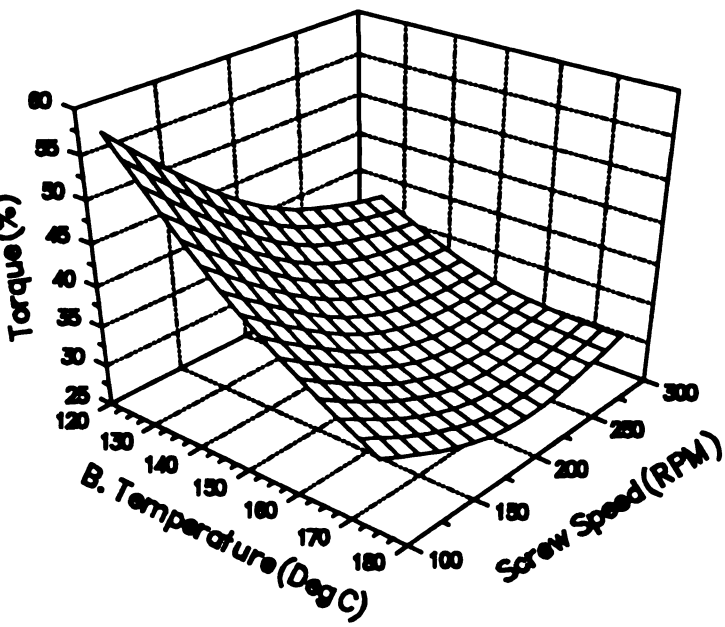

Figure 4.6 Percent Torque versus Barrel Temperature and Screw Speed at 25% Feed Moisture

4.8 Die Temperature

The die temperature (DT) as a function of feed moisture and barrel temperature is illustrated in Figure 4.7. The DT exceeds the set barrel temperature at most process conditions. As shown in Table 4.7, all the linear terms, two of the square terms except (moisture * moisture) and two of the interactions except (moisture * temperature) were significant ($P < 0.05$). the resulting polynomial after recalculation gives:

$$DT = 165.9 - 6.83x_1 + 14.76x_2 + 6.57x_3 + 0.94x_2^2 - 1.9x_3^2 - 1.56x_1x_3 - 0.69x_2x_3 \qquad (30)$$

Table 4.7 Estimated Regression Coefficients for Die Temperature Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	165.833	0.3036	546.187	0.000
x1	-6.830	0.1859	-36.736	0.000
x2	14.764	0.1859	79.406	0.000
x3	6.566	0.1859	35.317	0.000
x1*x1	0.056	0.2737	0.205	0.840
x2*x2	0.944	0.2737	3.449	0.003
x3*x3	-1.083	0.2737	-3.958	0.001
x1*x2	-0.083	0.2629	-0.317	0.755
x1*x3	-1.556	0.2629	-5.919	0.000
x2*x3	-0.694	0.2629	-2.640	0.016

s = 0.7437 R-sq = 99.8% R-sq(adj) = 99.7%

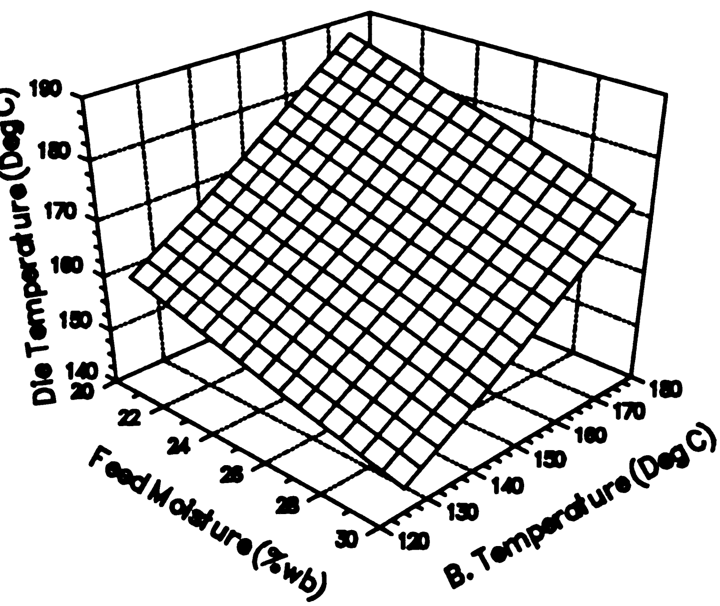

Figure 4.7 Die Temperature versus Feed Moisture and Barrel Temperature at 200 rpm Screw Speed

4.9 Die Pressure

A response surface for die pressure (DP) as a function of barrel temperature and screw speed is presented in Figure 4.8. All the linear and interaction terms were significant (Table 4.8) at $P < 0.05$. The only significant square term, however, was (screw speed x screw speed). The resulting polynomial using coded variables on recalculation gives:

$$DP = 3574 - 1030x_1 - 1259x_2 - 2021x_3 + 610x_3^2 + 564x_1x_2 + 953x_1x_3 + 599x_2x_3 \quad (31)$$

Table 4.8 Estimated Regression Coefficients for Die Pressure Using Coded variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	3534	147.21	24.004	0.000
x1	-1030	90.15	-11.428	0.000
x2	-1259	90.15	-13.969	0.000
x3	-2021	90.15	-22.419	0.000
x1*x1	162	132.69	1.221	0.236
x2*x2	-91	132.69	-0.687	0.500
x3*x3	616	132.69	4.639	0.000
x1*x2	564	127.49	4.425	0.000
x1*x3	953	127.49	7.476	0.000
x2*x3	599	127.49	4.698	0.000

s = 360.6 R-sq = 97.9% R-sq(adj) = 97.0%

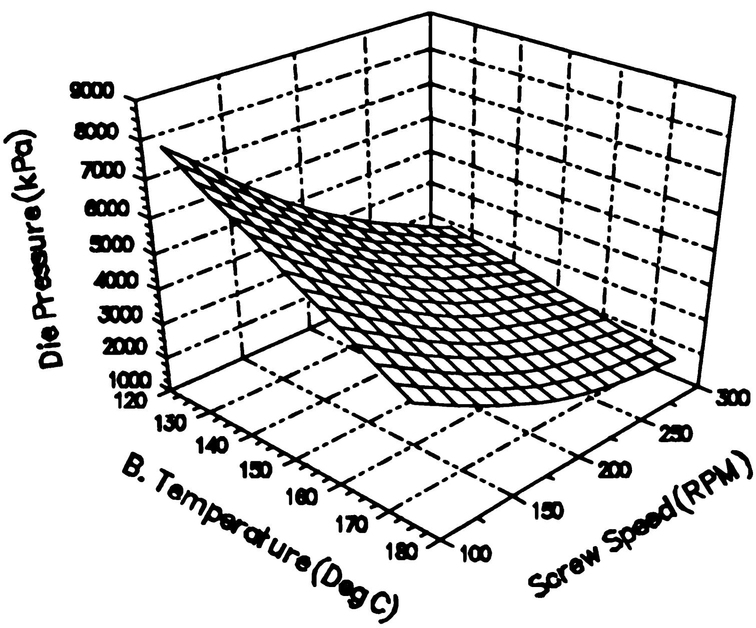

Figure 4.8 Die Pressure versus Barrel Temperature and Screw Speed at 25% Feed Moisture

Die pressure (DP) decreased with increasing feed moisture, barrel temperature and screw speed. The DP, according to Martelli (1983), is related to the feed rate and viscosity of dough as $DP = Q\mu/K_f$ where Q, μ and K_f are the output rate, melt viscosity and die conductance, respectively. In this experiment, the output rate and die conductance were constant. Therefore, the DP was proportional to the melt viscosity of the dough. Higher feed moisture and die temperature will certainly decrease the viscosity of the dough which may result in a lower DP. A higher screw speed caused a higher product temperature in the melting zone which, in turn, decreased the dough viscosity and resulted a lower DP. Decreasing DP with increasing screw speed has also been observed by other researchers such as Hsieh et al. (1991).

4.10 Specific Mechanical Energy

The specific mechanical energy (SME) input ranges from about 212 to 833 kJ/kg. This range of SME is in agreement with the range of 200-1000 kJ/kg reported for most co-rotating twin-screw extruders (Mange and Boissonnat, 1986). Figure 4.9 shows the effect of feed moisture and screw speed on SME. The regression coefficients for SME are given in Table 4.9. All linear, square and interaction terms were significant ($P < 0.05$). The resulting polynomial using coded values gives:

$$SME = 459.5 - 117.4x_1 - 98.7x_2 + 183.1x_3 + 14.7x_1^2 + 27.9x_2^2 + 21.6x_3^2 + 11x_1x_2 - 24.5x_1x_3 - 8.5x_2x_3 \quad (32)$$

Table 4.9 Estimated Regression Coefficients for Specific Mechanical Energy Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	459.5	3.409	134.822	0.000
x1	-117.4	2.087	-56.243	0.000
x2	-98.7	2.087	-47.283	0.000
x3	183.1	2.087	87.702	0.000
x1*x1	14.7	3.072	4.768	0.000
x2*x2	27.9	3.072	9.097	0.000
x3*x3	21.6	3.072	7.045	0.000
x1*x2	11.0	2.952	3.719	0.001
x1*x3	-24.5	2.952	-8.289	0.000
x2*x3	-8.5	2.952	-2.880	0.009
s = 8.349	R-sq = 99.9%		R-sq(adj) = 99.8%	

The SME increased with screw speed and it was the most important parameter affecting SME. Similar results were reported by Tsao et al. (1978); Fletcher et al. (1985); Della Valle et al. (1989); Hsieh et al. (1989, 1990) and Grenus et al. (1993).

The decrease of SME with increasing feed moisture could be explained by the lubricating effect of water. This result is in agreement with the findings of van Zuilichem et al. (1975) and Bruin et al. (1978) using corn grits, Faubion et al. (1982a) on starch, and Bhattacharya and Hanna (1987c) using corn gluten meal.

The increase in barrel temperature caused a decrease in SME requirement. This can be explained by the fact that higher temperature decreases dough viscosity which, in turn, decreases torque and SME. Similar trends of increasing SME when barrel temperature decreases were observed in twin-screw extruders (Antila et al., 1983; Meuser and van Lengerich, 1984a, and Meuser et al., 1987, 1989).

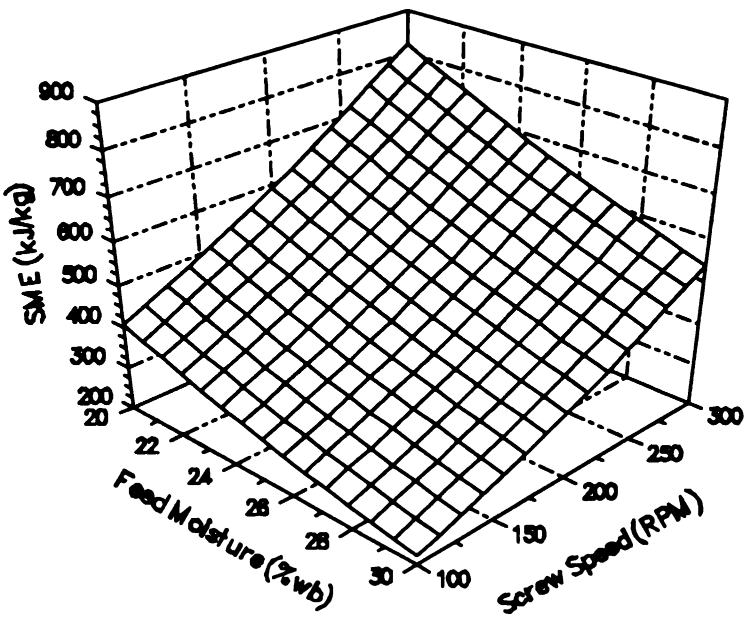

Figure 4.9 Specific Mechanical Energy versus Feed Moisture and Screw Speed at 150°C Barrel Temperature

4.11 Color

The regression coefficients for Hunter color parameters ('L'- lightness', 'a - redness' and 'b - yellowness') of teff flour extrudates are presented in Tables 4.10, 4.11 and 4.12 for 'L', 'a' and 'b', respectively. The only significant variables ($P < 0.05$) that affected color of the extrudates were feed moisture and screw speed. The response surfaces for 'L' and 'b' are shown in Figures 4.10 and 4.11, respectively. For color 'a', however, no response surface is given because of the low R^2 value ($R^2 = 0.47$) obtained from this work which showed that this response can not be adequately predicted by the parameters considered in the model. The resulting polynomials, after removal of non-significant terms and on recalculation using coded values gives:

$$L = 39.94 - 5.62x_1 + 1.89x_3 \quad (33)$$

$$a = 3.695 + 0.306x_1 - 0.29x_1x_3 \quad (34)$$

$$b = 10.59 - 0.859x_1 + 0.353x_3 \quad (35)$$

Table 4.10 Estimated Regression Coefficients for Color 'L' Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	40.450	0.6932	58.352	0.000
x1	-5.622	0.4245	-13.243	0.000
x2	0.584	0.4245	1.377	0.184
x3	1.894	0.4245	4.461	0.000
x1*x1	-1.122	0.6249	-1.795	0.088
x2*x2	0.603	0.6249	0.965	0.346
x3*x3	-0.428	0.6249	-0.685	0.501
x1*x2	0.306	0.6003	0.510	0.616
x1*x3	1.063	0.6003	1.770	0.092
x2*x3	-0.363	0.6003	-0.604	0.553
s = 1.698	R-sq = 91.1%		R-sq(adj) = 87.2%	

Table 4.11 Estimated Regression Coefficients for Color 'a' Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed)

Term	Coef	Stdev	t-ratio	P
Constant	3.6333	0.13084	27.769	0.000
x1	0.3062	0.08012	3.822	0.001
x2	-0.0656	0.08012	-0.819	0.422
x3	0.0344	0.08012	0.429	0.672
x1*x1	-0.0198	0.11794	-0.168	0.868
x2*x2	0.0115	0.11794	0.097	0.924
x3*x3	0.1240	0.11794	1.051	0.306
x1*x2	-0.1250	0.11331	-1.103	0.283
x1*x3	-0.2875	0.11331	-2.537	0.020
x2*x3	0.0313	0.11331	0.276	0.786
s = 0.3205	R-sq = 54.9%		R-sq(adj) = 34.6%	

Table 4.12 Estimated Regression Coefficients for Color 'b' Using Coded Variables (x1 = feed moisture, x2 = barrel temperature, x3 = screw speed).

Term	Coef	Stdev	t-ratio	P
Constant	10.6000	0.14715	72.034	0.000
x1	-0.8594	0.09011	-9.537	0.000
x2	0.0250	0.09011	0.277	0.784
x3	0.3531	0.09011	3.919	0.001
x1*x1	-0.0687	0.13264	-0.518	0.610
x2*x2	0.1000	0.13264	0.754	0.460
x3*x3	-0.0562	0.13264	-0.424	0.676
x1*x2	0.2063	0.12744	1.618	0.121
x1*x3	0.1375	0.12744	1.079	0.293
x2*x3	-0.0562	0.12744	-0.441	0.664
s = 0.3604	R-sq = 84.8%		R-sq(adj) = 77.9%	

The lightness (L) and yellowness (a) values decreased with increased feed moisture indicating that at higher moisture level, extrudates were darker as observed visually. The decrease in 'L' value of teff extrudates with the increase of moisture is consistent with the findings of Gujska and Khan (1991) for extruded bean high starch fractions, and Hsieh et al. (1990) on cottonseed using twin-screw extruder. The increase in darkness (lower L values) could be attributed to the compact and denser structure which resulted with increasing feed moisture (Hsieh et al., 1990). Another possible reason could be the occurrence of browning reactions between reducing sugars and water which resulted brown pigments. Increasing screw speed produced a lighter color (higher L value). Similar trends were reported for corn grits (Fletcher et al., 1985) extruded with twin-screw extruder. Higher screw speed resulted in a shorter residence time of teff extrudates in the extruder and therefore lighter extrudates were obtained from higher screw speed. The temperature of the barrel generally did not exert significant effect on product color. Similar conclusion was made by Hsieh et al. (1990).

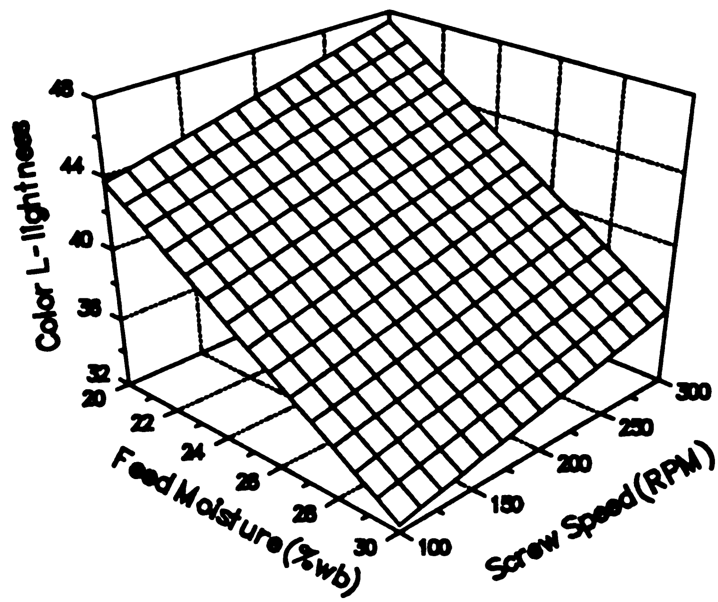

Figure 4.10 Color 'L' versus Feed Moisture and Screw Speed at 150°C Barrel Temperature

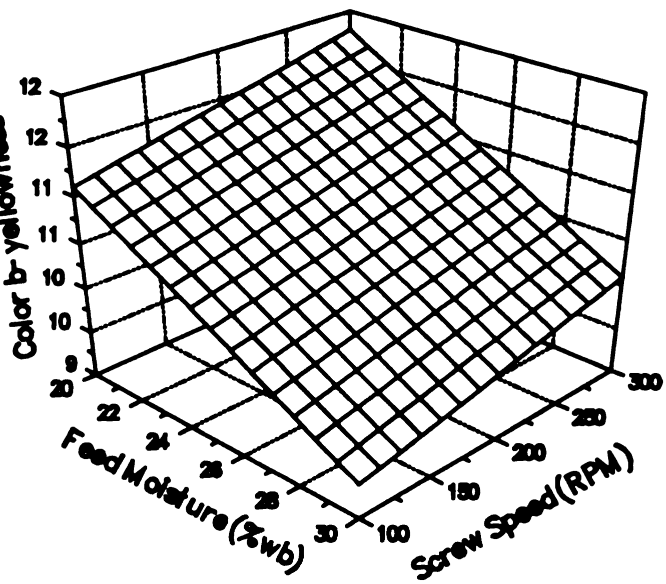

Figure 4.11 Color 'b' versus Feed Moisture and Screw Speed at 150°C Barrel Temperature

Table 4.13 Summary of Estimated Regression Coefficients and P values for Dependent Variables

Variables	ER	BD	WAI	WSI	PMC	%T	DT	DP	SME	L	b
Constant	2.732 0.000	0.194 0.000	6.083 0.000	6.526 0.000	8.565 0.000	32.83 0.000	165.9 0.000	3574 0.000	459.5 0.000	39.94 0.000	10.59 0.000
x_1	-0.179 0.000	0.056 0.000	0.264 0.000	-2.75 0.000	3.236 0.000	-5.68 0.000	-6.83 0.000	-1030 0.000	-117.4 0.000	-5.62 0.000	-0.859 0.000
x_2		-0.034 0.000	0.335 0.000	3.33 0.000	-0.809 0.000	-8.08 0.000	14.76 0.000	-1259 0.000	-98.7 0.000		
x_3		-0.031 0.000	-0.347 0.000	2.69 0.000	-0.766 0.000	-6.34 0.000	6.57 0.000	-2021 0.000	183.1 0.000	1.89 0.000	0.353 0.001
x_1^2	-0.089 0.0001	0.020 0.000		1.84 0.000	0.850 0.000				14.7 0.000		
x_2^2		-0.007 0.027	-0.346 0.003	2.55 0.000		2.40 0.002	0.94 0.003		27.9 0.000		
x_3^2		0.008 0.011			0.630 0.000	4.69 0.000	-1.90 0.001	610 0.000	21.6 0.000		
x_1x_2	0.081 0.001	-0.011 0.001			-0.350 0.003			564 0.000	11 0.001		
x_1x_3	0.630 0.005			-1.66 0.000		2.89 0.000	-1.56 0.000	953 0.000	-24.5 0.000		
x_2x_3	0.083 0.000		0.278 0.011	0.91 0.006		4.23 0.000	-0.69 0.016	599 0.000	-8.5 0.009		
R^2 (%)	89.69	98.50	79.59	95.28	98.96	97.47	99.78	97.72	99.68	86.49	80.87

CHAPTER V

SUMMARY AND CONCLUSIONS

Extrudate properties were influenced differently by different extrusion variables considered. An increase in feed moisture resulted in increased bulk density, water absorption index, and product moisture content, but in decreased expansion ratio, water solubility index, percent torque, die temperature, die pressure, specific mechanical energy, and lower 'L' and 'b' color values. An increase in barrel temperature resulted in decreased bulk density, product moisture content, percent torque, die pressure, and specific mechanical energy but in increased water absorption index, water solubility index, die temperature, and values of color 'L' and 'b'. Increasing screw speed resulted increased water solubility index, die temperature, and specific mechanical energy, but caused a decrease in bulk density, water absorption index, product moisture content, percent torque, and die pressure.

The square terms of feed moisture content significantly affected bulk density, water solubility index, product moisture content, and specific mechanical energy. The square terms of barrel temperature significantly influenced all the dependent variables considered except expansion ratio and die pressure. The square terms of screw speed influenced bulk density, percent torque, die temperature, die pressure, and specific mechanical energy.

The interaction term of moisture and temperature was significant for expansion ratio, bulk density, product moisture content, die pressure, and specific mechanical energy whereas, the interaction term of moisture and screw speed was significant for expansion ratio, water solubility index, die temperature, die pressure, and specific mechanical energy. The dependent variables significantly influenced by the interactions of temperature and screw speed were expansion ratio, water absorption index, water solubility index, percent torque, die temperature, die pressure, and specific mechanical energy.

The overall results show that teff flour can successfully be processed using a twin-screw extruder to produce product properties similar to other extruded products currently used in the food industry. The high correlation of the models with the measured data shows that the calculated second order polynomials are sufficiently accurate and valuable for predicting properties of teff extrudates and extruder response with in the range of variables considered.

CHAPTER VI

SUGGESTIONS FOR FURTHER RESEARCH

Product characteristics in extrusion cooking are known to be determined by many additional factors than considered in this study. Therefore, in order to gain complete understanding and appreciation of teff extrusion process, other variables including physical characteristics and physicochemical changes of the raw material as a result of the process such as particle size, rheology, quality factors of starch (amylose, amylopectin, extent of starch damage) and sensory assessment (texture, flavor, overall acceptability), and additional extruder characteristics such as different screw configurations need to be studied.

Another area of interest could be to produce teff products by extrusion cooking to a suitable form to be used by humans. The product may well be blended with other cereals like wheat or rice resulting a nutritionally improved product. The extruded product in this work had a mild flavor and attractive color. The measured functional product properties of teff extrudates also indicated that teff flour has the capability to be used as breakfast cereal or snack food. This may help to meet the diverse and particular taste of a range of cultures and individuals.

APPENDICES

APPENDIX A
RAW DATA TABLE FOR TWIN-SCREW EXTRUSION OF TEFF FLOUR

M.C	B.T	SS	ER	BD	WAI	WSI	PMC	%T	DT	DP	SME	L	a	b
1	1	0	2.597	0.2172	6.311	11.011	11.53	24.143	174	2321	306.83	36.84	3.85	10.05
1	1	0	2.515	0.2252	6.560	10.126	11.68	24.330	174	2321	309.3	31.25	4.10	10.30
0	1	-1	2.660	0.1985	5.870	9.033	9.16	32.875	175	3999	230.13	39.95	3.65	10.4
0	1	-1	2.646	0.1831	5.875	9.918	9.04	33.333	175.2	3723	233.33	40.5	3.9	10.5
0	1	1	2.811	0.1335	6.079	16.179	7.86	27.25	186	1241.1	572.25	43	3.67	10.6
0	1	1	2.798	0.1318	6.187	16.251	7.685	27.5	186	1551.4	577.5	44.05	3.50	10.95
-1	1	0	2.795	0.1275	5.841	17.052	5.458	33.0	189	2643.1	509.31	44.2	3.1	11
-1	1	0	2.632	0.1245	5.856	17.011	5.36	33.5	188	2775	517.02	47.15	3.3	11.5
0	0	0	2.730	0.1921	6.132	5.958	8.159	33.0	165	3619.9	462	38.45	3.7	10.3
0	0	0	2.736	0.1820	5.687	6.378	8.245	32.76	166	3637.1	458.5	38.47	3.96	10.2
1	-1	0	2.431	0.3101	5.405	5.399	13.979	36.83	145	3226.9	468.12	32.25	4.1	8.95
1	-1	0	2.376	0.3111	5.971	5.510	14.172	37.0	144.7	3516.5	470.24	34.9	4.5	10.25
0	-1	1	2.727	0.2023	4.994	7.827	8.983	38.2	158	3010.8	802.2	41.15	3.85	10.8
0	-1	1	2.668	0.2044	5.205	7.620	8.748	38.33	157.3	3102.8	804.93	42.38	3.55	11.1
0	-1	-1	2.907	0.2545	5.959	4.701	10.878	60.5	144	8067.2	423.5	36.25	3.95	10.25
0	-1	-1	2.848	0.2536	5.943	4.554	11.019	61.36	146	7768.4	429.3	37.76	4.1	10.55
-1	-1	0	2.946	0.1673	4.885	8.945	6.59	46.57	160	6033.1	718.76	45.6	2.9	11.25
-1	-1	0	2.822	0.1776	4.852	8.805	6.337	46.5	159	5998.7	717.66	47.3	3.15	11.75
0	0	0	2.680	0.2055	5.892	5.974	8.894	33.0	165	3516.5	462	42	3.95	11
0	0	0	2.658	0.1961	6.120	5.852	8.731	32.6	166	3449.2	456.4	42.6	3.7	11.05
1	0	-1	2.374	0.3202	6.790	4.439	13.67	33.475	153	4171.5	212.09	30.65	3.85	8.8
1	0	-1	2.412	0.3122	6.839	4.609	13.87	33.986	154.7	4361.1	213.93	31.27	4	8.95
1	0	1	2.551	0.2272	5.829	9.353	12.565	28.0	164	1723.8	533.79	36.7	3.86	10.2
1	0	1	2.461	0.2419	5.640	4.719	12.285	28.25	165	1778.9	538.55	36.4	3.65	10.05
0	0	0	2.735	0.1905	6.075	5.970	8.861	33.24	166	3482	462	39.8	3.45	10.4
0	0	0	2.648	0.1980	6.469	5.538	8.725	32.62	165	3447.5	456.4	41.6	3.05	10.65
-1	0	-1	2.992	0.1930	6.590	7.070	7.647	52.78	166	8784.2	407.27	42.8	3	10.9
-1	0	-1	2.84	0.2032	6.361	7.458	7.836	53.42	163	8770.4	405.9	43.9	3.3	11.30
-1	0	1	2.798	0.135	5.189	16.328	6.172	35.5	180	2716.6	821.8	43.75	4.1	11.75
-1	0	1	2.758	0.141	5.556	16.470	6.573	36	179.2	2183.4	833.4	45.7	4.15	11.85

APPENDIX B

ANOVA AND STEPWISE REGRESSION TABLES FOR DEPENDENT VARIABLES

Analysis of Variance for ER

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.729362	0.729362	0.081040	25.53	0.000
Linear	3	0.519005	0.519005	0.173002	54.50	0.000
Square	3	0.071503	0.071503	0.023834	7.51	0.001
Interaction	3	0.138855	0.138855	0.046285	14.58	0.000
Residual Error	20	0.063492	0.063492	0.003175		
Lack-of-Fit	3	0.008636	0.008636	0.002879	0.89	0.465
Pure Error	17	0.054857	0.054857	0.003227		
Total	29	0.792855				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is ER on 9 predictors, with N = 30

Step	1	2	3	4	5
Constant	2.685	2.732	2.732	2.732	2.732
x1	-0.179	-0.179	-0.179	-0.179	-0.179
T-Ratio	-7.18	-7.93	-8.99	-10.66	-12.28
x4		-0.089	-0.089	-0.089	-0.089
T-Ratio		-2.68	-3.03	-3.60	-4.15
x9			0.083	0.083	0.083
T-Ratio			2.94	3.49	4.02
x7				0.081	0.081
T-Ratio				3.40	3.92
x8					0.063
T-Ratio					3.04
S	0.0998	0.0904	0.0798	0.0673	0.0583
R-Sq	64.80	72.18	79.13	85.73	89.69

Note: x4 = x1*x1, x5 = x2*x2, x6 = x3*x3
x7 = x1*x2, x8 = x1*x3, x9 = x2*x3

Analysis of Variance for BD

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.089043	0.089043	0.009894	181.40	0.000
Linear	3	0.084096	0.084096	0.028032	513.96	0.000
Square	3	0.003765	0.003765	0.001255	23.01	0.000
Interaction	3	0.001182	0.001182	0.000394	7.23	0.002
Residual Error	20	0.001091	0.001091	0.000055		
Lack-of-Fit	3	0.000358	0.000358	0.000119	2.77	0.074
Pure Error	17	0.000733	0.000733	0.000043		
Total	29	0.090134				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is BD on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	0.2053	0.2053	0.2053	0.1947	0.1947	0.1901	0.1941
x1	0.0560	0.0560	0.0560	0.0560	0.0560	0.0560	0.0560
T-Ratio	5.93	7.90	14.70	20.20	23.66	26.38	28.61
x2		-0.0337	-0.0337	-0.0337	-0.0337	-0.0337	-0.0337
T-Ratio		-4.76	-8.85	-12.17	-14.25	-15.89	-17.23
x3			-0.0313	-0.0313	-0.0313	-0.0313	-0.0313
T-Ratio			-8.22	-11.30	-13.23	-14.75	-16.00
x4				0.0199	0.0199	0.0205	0.0200
T-Ratio				4.91	5.75	6.58	6.94
x7					-0.0107	-0.0107	-0.0107
T-Ratio					-3.21	-3.58	-3.88
x6						0.0081	0.0076
T-Ratio						2.61	2.65
x5							-0.0065
T-Ratio							-2.25
S	0.0378	0.0284	0.0152	0.0111	0.00947	0.00849	0.00783
R-Sq	55.69	75.89	93.30	96.59	97.61	98.16	98.50

Analysis of Variance for WAI

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	6.3914	6.3914	0.71016	8.96	0.000
Linear	3	4.8343	4.8343	1.61142	20.34	0.000
Square	3	0.9116	0.9116	0.30386	3.84	0.026
Interaction	3	0.6456	0.6456	0.21520	2.72	0.072
Residual Error	20	1.5843	1.5843	0.07922		
Lack-of-Fit	3	0.9073	0.9073	0.30245	7.60	0.002
Pure Error	17	0.6770	0.6770	0.03982		
Total	29	7.9757				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is WAI on 9 predictors, with N = 30

Step	1	2	3	4	5
Constant	5.899	5.899	5.899	6.083	6.083
x3	-0.347	-0.347	-0.347	-0.347	-0.347
T-Ratio	-2.98	-3.49	-3.99	-4.63	-5.33
x2		0.335	0.335	0.335	0.335
T-Ratio		3.38	3.86	4.48	5.15
x1			0.264	0.264	0.264
T-Ratio			3.03	3.52	4.05
x5				-0.346	-0.346
T-Ratio				-3.16	-3.63
x9					0.278
T-Ratio					3.02
S	0.465	0.397	0.348	0.300	0.260
R-Sq	24.11	46.68	60.61	71.84	79.59

Analysis of Variance for WSI

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	521.899	521.899	57.989	82.26	0.000
Linear	3	413.248	413.248	137.749	195.42	0.000
Square	3	75.468	75.468	25.156	35.69	0.000
Interaction	3	33.183	33.183	11.061	15.69	0.000
Residual Error	20	14.098	14.098	0.705		
Lack-of-Fit	3	2.056	2.056	0.685	0.97	0.431
Pure Error	17	12.042	12.042	0.708		
Total	29	535.997				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is WSI on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	8.869	8.869	8.869	7.580	6.526	6.526	6.526
x2	3.33	3.33	3.33	3.33	3.33	3.33	3.33
T-Ratio	3.72	4.48	6.12	7.48	8.88	11.29	12.41
x1		-2.75	-2.75	-2.75	-2.75	-2.75	-2.75
T-Ratio		-3.70	-5.06	-6.18	-7.34	-9.33	-10.25
x3			2.69	2.69	2.69	2.69	2.69
T-Ratio			4.94	6.04	7.17	9.12	10.02
x5				2.42	2.55	2.55	2.55
T-Ratio				3.71	4.64	5.90	6.48
x4					1.84	1.84	1.84
T-Ratio					3.36	4.27	4.69
x8						-1.66	-1.66
T-Ratio						-3.97	-4.37
x9							0.91
T-Ratio							2.40
S	3.58	2.97	2.17	1.78	1.50	1.18	1.07
R-Sq	33.04	55.58	77.10	85.24	89.95	94.04	95.28

Analysis of Variance for PMC

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	196.511	196.511	21.8346	250.56	0.000
Linear	3	187.368	187.368	62.4561	716.72	0.000
Square	3	7.850	7.850	2.6166	30.03	0.000
Interaction	3	1.293	1.293	0.4310	4.95	0.010
Residual Error	20	1.743	1.743	0.0871		
Lack-of-Fit	3	0.951	0.951	0.3170	6.80	0.003
Pure Error	17	0.792	0.792	0.0466		
Total	29	198.254				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is PMC on 9 predictors, with N = 30

Step	1	2	3	4	5	6
Constant	9.357	9.357	9.357	8.928	8.565	8.565
x1	3.236	3.236	3.236	3.236	3.236	3.236
T-Ratio	12.36	14.94	20.00	26.31	36.23	43.30
x2		-0.809	-0.809	-0.809	-0.809	-0.809
T-Ratio		-3.73	-5.00	-6.58	-9.05	-10.82
x3			-0.766	-0.766	-0.766	-0.766
T-Ratio			-4.73	-6.23	-8.57	-10.24
x4				0.80	0.85	0.85
T-Ratio				4.47	6.49	7.75
x6					0.63	0.63
T-Ratio					4.84	5.78
x7						-0.35
T-Ratio						-3.36
S	1.05	0.866	0.647	0.492	0.357	0.299
R-Sq	84.50	89.78	94.51	96.95	98.46	98.96

Analysis of Variance for %T

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	2609.40	2609.40	289.934	86.00	0.000
Linear	3	2204.30	2204.30	734.766	217.96	0.000
Square	3	195.11	195.11	65.037	19.29	0.000
Interaction	3	209.99	209.99	69.998	20.76	0.000
Residual Error	20	67.42	67.42	3.371		
Lack-of-Fit	3	66.36	66.36	22.120	353.38	0.000
Pure Error	17	1.06	1.06	0.063		
Total	29	2676.83				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is %T on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	36.61	36.61	36.61	34.20	34.20	34.20	32.83
x2	-8.08	-8.08	-8.08	-8.08	-8.08	-8.08	-8.08
T-Ratio	-4.24	-5.34	-7.58	-9.03	-11.90	-14.75	-18.44
x3		-6.34	-6.34	-6.34	-6.34	-6.34	-6.34
T-Ratio		-4.19	-5.95	-7.08	-9.34	-11.57	-14.46
x1			-5.68	-5.68	-5.68	-5.68	-5.68
T-Ratio			-5.33	-6.35	-8.36	-10.36	-12.96
x6				4.52	4.52	4.52	4.69
T-Ratio				3.45	4.54	5.63	7.29
x9					4.23	4.23	4.23
T-Ratio					4.41	5.46	6.83
x8						2.89	2.89
T-Ratio						3.72	4.66
x5							2.40
T-Ratio							3.73
S	7.63	6.05	4.26	3.58	2.72	2.19	1.75
R-Sq	39.06	63.08	82.35	88.04	93.38	95.87	97.47

Analysis of Variance for DT

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	4963.64	4963.64	551.52	997.12	0.000
Linear	3	4923.82	4923.82	1641.27	3E+03	0.000
Square	3	16.54	16.54	5.51	9.96	0.000
Interaction	3	23.29	23.29	7.76	14.03	0.000
Residual Error	20	11.06	11.06	0.55		
Lack-of-Fit	3	8.58	8.58	2.86	19.54	0.000
Pure Error	17	2.49	2.49	0.15		
Total	29	4974.71				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is DT on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	165.8	165.8	165.8	165.8	166.4	165.9	165.9
x2	14.76	14.76	14.76	14.76	14.76	14.76	14.76
T-Ratio	8.10	11.27	42.21	52.60	62.32	73.14	82.99
x1		-6.83	-6.83	-6.83	-6.83	-6.83	-6.83
T-Ratio		-5.22	-19.53	-24.34	-28.83	-33.84	-38.39
x3			6.57	6.57	6.57	6.57	6.57
T-Ratio			18.78	23.40	27.72	32.53	36.91
x8				-1.56	-1.56	-1.56	-1.56
T-Ratio				-3.92	-4.64	-5.45	-6.19
x6					-1.15	-1.09	-1.09
T-Ratio					-3.33	-3.67	-4.16
x5						0.94	0.94
T-Ratio						3.17	3.60
x9							-0.69
T-Ratio							-2.76
S	7.29	5.24	1.40	1.12	0.948	0.807	0.712
R-Sq	70.10	85.11	98.98	99.37	99.57	99.70	99.78

Analysis of Variance for DP

Source	DF	Seq SS	Adj SS	Adj MS	F	P5
Regression	9	123446256	123446256	13716251	105.49	0.000
Linear	3	107706816	107706816	35902272	276.11	0.000
Square	3	3056308	3056308	1018769	7.84	0.001
Interaction	3	12683130	12683130	4227710	32.51	0.000
Residual Error	20	2600552	2600552	130028		
Lack-of-Fit	3	2222800	2222800	740933	33.34	0.000
Pure Error	17	377751	377751	22221		
Total	29	126046808S				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is DP on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	3900	3900	3900	3900	3900	3574	3574
x3	-2021	-2021	-2021	-2021	-2021	-2021	-2021
T-Ratio	-5.49	-7.07	-9.63	-12.15	-13.83	-16.65	-22.37
x2		-1259	-1259	-1259	-1259	-1259	-1259
T-Ratio		-4.40	-6.00	-7.57	-8.62	-10.38	-13.94
x1			-1030	-1030	-1030	-1030	-1030
T-Ratio			-4.91	-6.19	-7.05	-8.49	-11.40
x8				953	953	953	953
T-Ratio				4.05	4.61	5.55	7.46
x9					599	599	599
T-Ratio					2.90	3.49	4.69
x6						610	610
T-Ratio						3.44	4.61
x7							564
T-Ratio							4.41
S	1472	1144	840	666	585	485	361
R-Sq	51.85	71.98	85.45	91.22	93.49	95.70	97.72

Analysis of Variance for SME

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	928391	928391	103155	1E+03	0.000
Linear	3	912546	912546	304182	4E+03	0.000
Square	3	9514	9514	3171	45.49	0.000
Interaction	3	6332	6332	2111	30.28	0.000
Residual Error	20	1394	1394	70		
Lack-of-Fit	3	1199	1199	400	34.82	0.000
Pure Error	17	195	195	11		
Total	29	929786				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is SME on 9 predictors, with N = 30

Step	1	2	3	4	5	6	7
Constant	493.8	493.8	493.8	480.3	480.3	468.6	459.5
x3	183.1	183.1	183.1	183.1	183.1	183.1	183.1
T-Ratio	6.18	9.15	28.44	32.83	41.02	52.23	63.38
x1		-117.4	-117.4	-117.4	-117.4	-117.4	-117.4
T-Ratio		-5.86	-18.24	-21.05	-26.30	-33.49	-40.65
x2			-98.7	-98.7	-98.7	-98.7	-98.7
T-Ratio			-15.33	-17.70	-22.11	-28.16	-34.17
x5				25.4	25.4	26.8	27.9
T-Ratio				3.11	3.88	5.21	6.57
x8					-24.5	-24.5	-24.5
T-Ratio					-3.88	-4.94	-5.99
x6						20.5	21.6
T-Ratio						3.99	5.09
x4							14.7
T-Ratio							3.45
S	119	80.1	25.7	22.3	17.9	14.0	11.6
R-Sq	57.67	81.38	98.15	98.66	99.18	99.51	99.68

Analysis of Variance for 'L'

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	593.33	593.33	65.926	22.87	0.000
Linear	3	568.53	568.53	189.511	65.73	0.000
Square	3	13.97	13.97	4.656	1.61	0.218
Interaction	3	10.83	10.83	3.611	1.25	0.317
Residual Error	20	57.66	57.66	2.883		
Lack-of-Fit	3	11.47	11.47	3.822	1.41	0.275
Pure Error	17	46.20	46.20	2.718		
Total	29	651.00				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is L on 9 predictors, with N = 30

Step	1	2
Constant	39.94	39.94
x1	-5.62	-5.62
T-Ratio	-9.87	-12.46
x3		1.89
T-Ratio		4.20
S	2.28	1.80
R-Sq	77.68	86.49

Analysis of Variance for 'a'

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	2.5025	2.5025	0.27805	2.71	0.031
Linear	3	1.5884	1.5884	0.52948	5.15	0.008
Square	3	0.1200	0.1200	0.03999	0.39	0.762
Interaction	3	0.7941	0.7941	0.26469	2.58	0.082
Residual Error	20	2.0543	2.0543	0.10271		
Lack-of-Fit	3	1.1322	1.1322	0.37740	6.96	0.003
Pure Error	17	0.9221	0.9221	0.05424		
Total	29	4.5567				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is a on 9 predictors, with N = 30

Step	1	2
Constant	3.695	3.695
x1	0.306	0.306
T-Ratio	3.71	4.11
x8		-0.29
T-Ratio		-2.73
S	0.330	0.298
R-Sq	32.93	47.44

Analysis of Variance for 'b'

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	14.4812	14.4812	1.60903	12.38	0.000
Linear	3	13.8216	13.8216	4.60719	35.46	0.000
Square	3	0.1428	0.1428	0.04760	0.37	0.778
Interaction	3	0.5169	0.5169	0.17229	1.33	0.294
Residual Error	20	2.5984	2.5984	0.12992		
Lack-of-Fit	3	0.5534	0.5534	0.18448	1.53	0.242
Pure Error	17	2.0450	2.0450	0.12029		
Total	29	17.0797				

Stepwise Regression

F-to-Enter: 4.00 F-to-Remove: 4.00

Response is b on 9 predictors, with N = 30

Step	1	2
Constant	10.59	10.59
x1	-0.859	-0.859
T-Ratio	-7.93	-9.88
x3		0.353
T-Ratio		4.06
S	0.434	0.348
R-Sq	69.18	80.87

APPENDIX C

MOTOR NAMEPLATE DATA FOR ZSK-30 EXTRUDER

Model:	GE DC 300
Hp:	15
Rpm:	2500
Max Torque:	90 NM per output shaft
Overall Gear Ratio:	5 : 1
Screw Rpm:	500

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