This is to certify that the

thesis entitled

A Predictive Model for Pressure Drop
in Food Extruder Dies

presented by

Murray Donald Howkins

has been accepted towards fulfillment
of the requirements for

M.S. degree in Agricultural Engineering

Ronnie G. Morgan
Major professor

Date Oct 1, 1987

A PREDICTIVE MODEL FOR PRESSURE DROP IN FOOD EXTRUDER DIES

By

Murray Donald Howkins

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Master of Science

Department of Agricultural Engineering

1987

ABSTRACT

A PREDICTIVE MODEL FOR PRESSURE DROP IN FOOD EXTRUDER DIES

By

Murray Donald Howkins

A model based on a generalized Reynold's number and material viscoelastic properties has been developed for predicting entrance pressure drop through mulitiple hole food extruder dies. The model was applied to data collected during twin-screw extrusion of potato dough, defatted soy dough, and an inert food dough, and gave accurate prediction of entrance pressure drop. This model, combined with previous models for predicting die hole pressure drop, provides a method for assessing total die pressure drop in an extruder for use in scale-up and die modification applications.

ACKNOWLEDGEMENTS

The author expresses sincere gratitude to the following people for their input on this thesis:

Dr. Ronnie G. Morgan for his invaluable professional and personal guidance during this graduate program. His continued encouragement and optimism were very much appreciated.

Dr. Fred W. Bakker-Arkema, Dr. Robert Y. Ofoli and Dr. Mark A. Uebersax for their added expertise to this project as well as encouragement and excellent advice for career plans including plans for future overseas work.

The Food Engineering extrusion team for their assistance in data collection and analysis. Special thanks goes to Barb Christensen, Kevin Evans, Gary Garfield, John Keenan, D'Anne Larsen, and John Leen.

The entire Food Engineering/Agricultural Engineering Dept. at Michigan State University for their personal friendship and advice.

Rudy Leschke of Nabisco Brands Inc. for his valuable input on the methodology of this study.

Kevin Rose and Kirk Dolan, fellow Agricultural Engineering graduate students, who helped, encouraged, and befriended the author throughout his graduate program.

The Author's parents, John and Beryl Howkins, for their continued support, prayers, patience, and encouragement throughout the author's academic career.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

CHAPTER | Page

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

NOMENCLATURE

a	Empirical constant
b	Moisture content adjustment for genralized viscosity
b_i	Empirical exponent for π_i term
D_c	Diameter of barrel conduit (m)
D_d	Die Diameter (m)
E_v	Activation energy (cal/g mol)
F	Shape Factor
k	Coefficient in eqn 24
K	Constant used in equating N_1 (eqn 18) (Pa)
L	Die length (m)
L_e	Die end length (equivalent length added to die hole length accounting for end pressure drop (m)
L_{ent}	Entry length region before fully developed flow (m)
m	Power law consistency coefficient (Pa-sec^n)
$\dot{M}$	Mass rate (kg/hr)
MC	Moisture content (percent wet basis)
MC_R	Reference moisture content (percent wet basis)
n	Power law flow behavior index
n_d	Number of die holes
N_1	Primary normal stress differecne (Pa)
p	Exponent used in equating N_1 (Eqn. 17)
ΔP_{adj}	Total pressure adjusted for temperature (Pa)
ΔP_{dhole}	Die hole pressure drop (Pa)
ΔP_e	End pressure drop (Pa)
ΔP_{ent}	Entrance pressure drop (Pa)
ΔP_{ex}	Exit pressure drop (Pa)
ΔP_{obs}	Total die pressure drop at observed temperature (Pa)

ΔP_T	Total predicted pressure drop (Pa)
Q	Volumetric flow rate (m^3/s)
r_h	Hydraulic radius of die hole (m)
R	Die radius (m)
Re_{gen}	Generalized reynold's number
R	Universal gas constant (1.987 cal/gmol-^oK)
s	Die hole center spacing (m)
T	Temperature (^oK)
T_R	Reference temperature (^oK)
V	Average velocity in die (m/s)
α	coefficient in eqn 24.
α	Die entrance angle (deg)
β	Jet swell ratio (extrudate dia./die dia.)
β_2	coefficient used in eqn 24.
β'	slip coefficient
γ	True shear rate (s^{-1})
Γ	Apparent shear rate (s^{-1})
λ	Time constant (s)
λ_a	Proposed alternative time constant (s)
η	Viscosity (Pa s)
π_i	Independent dimensionless term (Table 2)
ρ	Density of material at the die (kg/m^3)
τ_w	Shear stress at the wall (Pa)
Ψ	Temperature-time history (^oC-s)
Φ	Shear history

CHAPTER I.

INTRODUCTION

The uniqueness and efficiency of extrusion has led to its wide acceptance for manufacturing several different types of food products. Single screw extrusion originated in the mid 1930's with development of the Collet extruder for producing puffed corn curls (Harper, 1981). Then, in the mid 1950's, single screw cooking extrusion grew rapidly as an efficient means of producing expanded pet foods. In the late 1970's twin-screw extrusion began to receive moderate attention in the food industry as an improved extrusion technology for specific applications. Today, twin-screw extrusion technologies are growing at significant rates and are used to manufacture a host of various food products. Among these products are breakfast cereals, snack foods, pet food, beverage powders and bread dough.

Use of extruders in the food industry is constrained due to lack of adequate knowledge about how process conditions affect machine performance and product quality. This lack of knowledge restricts engineering scale-up of the processes. Typical scale-up is still an art, relying on personal expertise and experience. This is largely due to geometric complexity, irreversible physicochemical reactions and non-Newtonian behavior of foods.

One critical phenomenon in extrusion scale-up involves the pressure drop versus flow rate (ΔP vs. Q) relationship through the die assembly. Changes in this relationship directly affect extruder performance by changing residence time, percent screw fill, and power requirements. These in turn alter shear history, thermal history, and thus viscosity. These parameters directly affect extrudate quality, especially in starch or protein products where starch gelatinization and/or protein denaturation significantly alter the product properties.

A common need is to alter extrudate size and/or shape without affecting process history within the extruder. Therefore, one needs to change die assemblies without altering its overall ΔP vs Q relationship. A major problem in achieving this goal is the lack of reliable methods for predicting die entrance pressure drop for non-Newtonian food materials flowing through multiple non-circular holes. Hence the objectives for this investigation are:

1. To develop an engineering analysis technique for predicting entrance pressure loss in food extruder dies as a function of die geometry, material rheology, and process conditions.
2. To use experimental data for plastic polymers and biological materials to verify the proposed technique.

Although total ΔP vs. Q is the primary die design factor affecting extruder performance, practitioners should note that parameters such as maximum shear rate and die roughness may also impact product quality (Harper,1986). The present study only emphasizes the assessment of pressure drop phenomenon of extruder dies, not product quality.

CHAPTER II.

REVIEW OF LITERATURE

DISCUSSION OF NEED

An extruder's total output is directly affected by the pressure drop-flow rate relationship of the screw and die. In a screw extruder, net flow is equal to the drag flow caused by the forward thrust of the screws, minus the back flow caused by the die pressure (Harper, 1981). The point at which net flow is equal to the die flow for a given product rate is known as the extruder operating point. Figure 1 depicts how a change in die ΔP vs. Q changes the extruder's operating point. Changing from die #1 to die #2 (Figure 1) causes a change in the die ΔP vs. Q, thus shifting the operating point.

Shifting the extruder operating point changes process parameters such as residence time, power input and percent screw fill. These parameters in turn affect process kinetics. Figure 2 schematically illustrates how die ΔP vs. Q characteristics can affect extruder performance and extrudate quality. Note that quality is application specific and denotes the desired physical and physicochemical properties such as texture, puffing, percent gelatinization or denaturation.

Change in die geometry affects the extruder power requirement. While extruding a nonreactive non-Newtonian dough, the author observed a 40 to 50 percent increase in power input when changing die L/D from one to eight on a twin-screw extruder. Harper (1981) shows that total power of a single-screw extruder is a function of extruder die pressure.

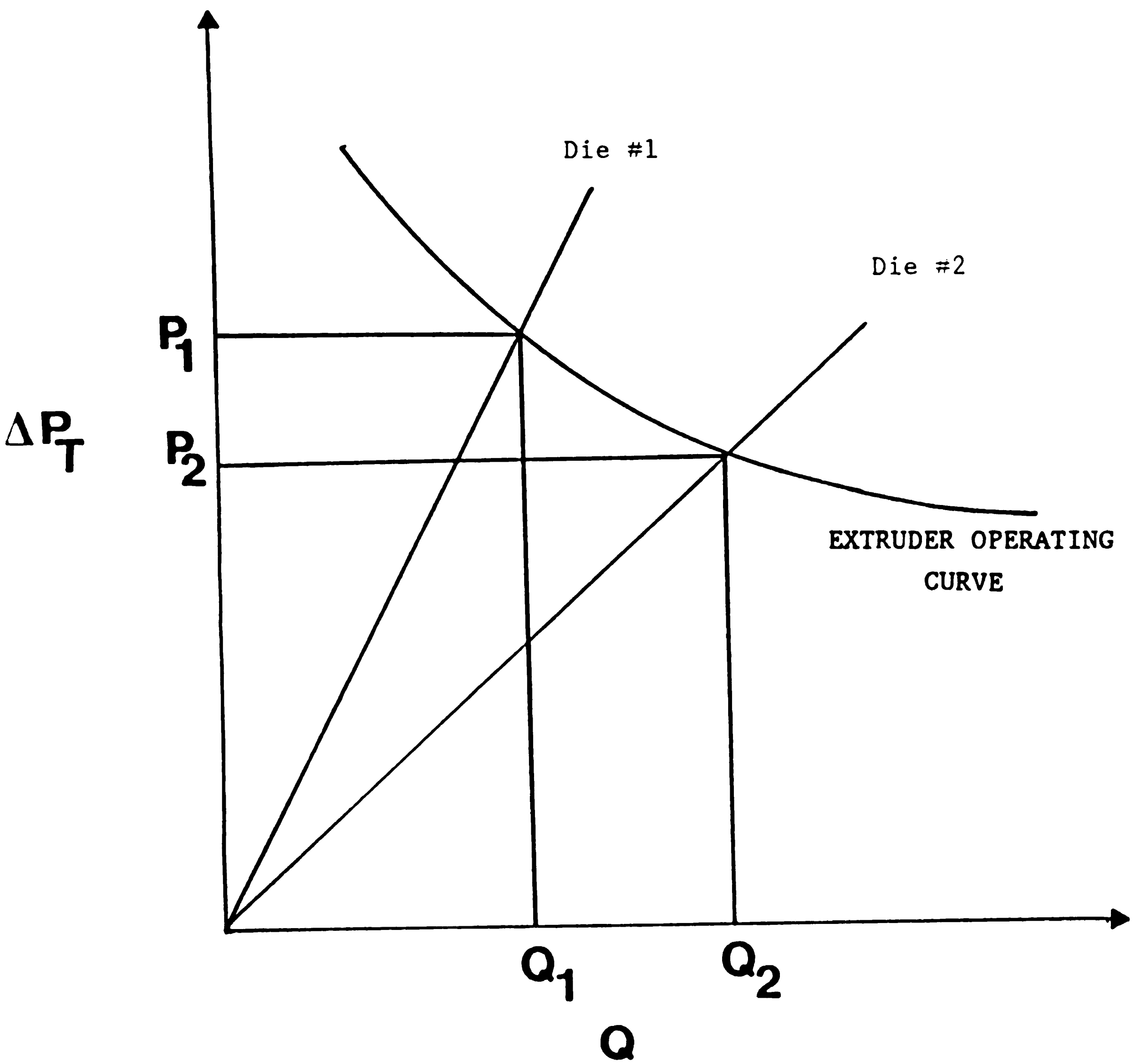


Figure 1. Effects of changes in die ΔP vs. Q relationships on extruder operating performance.

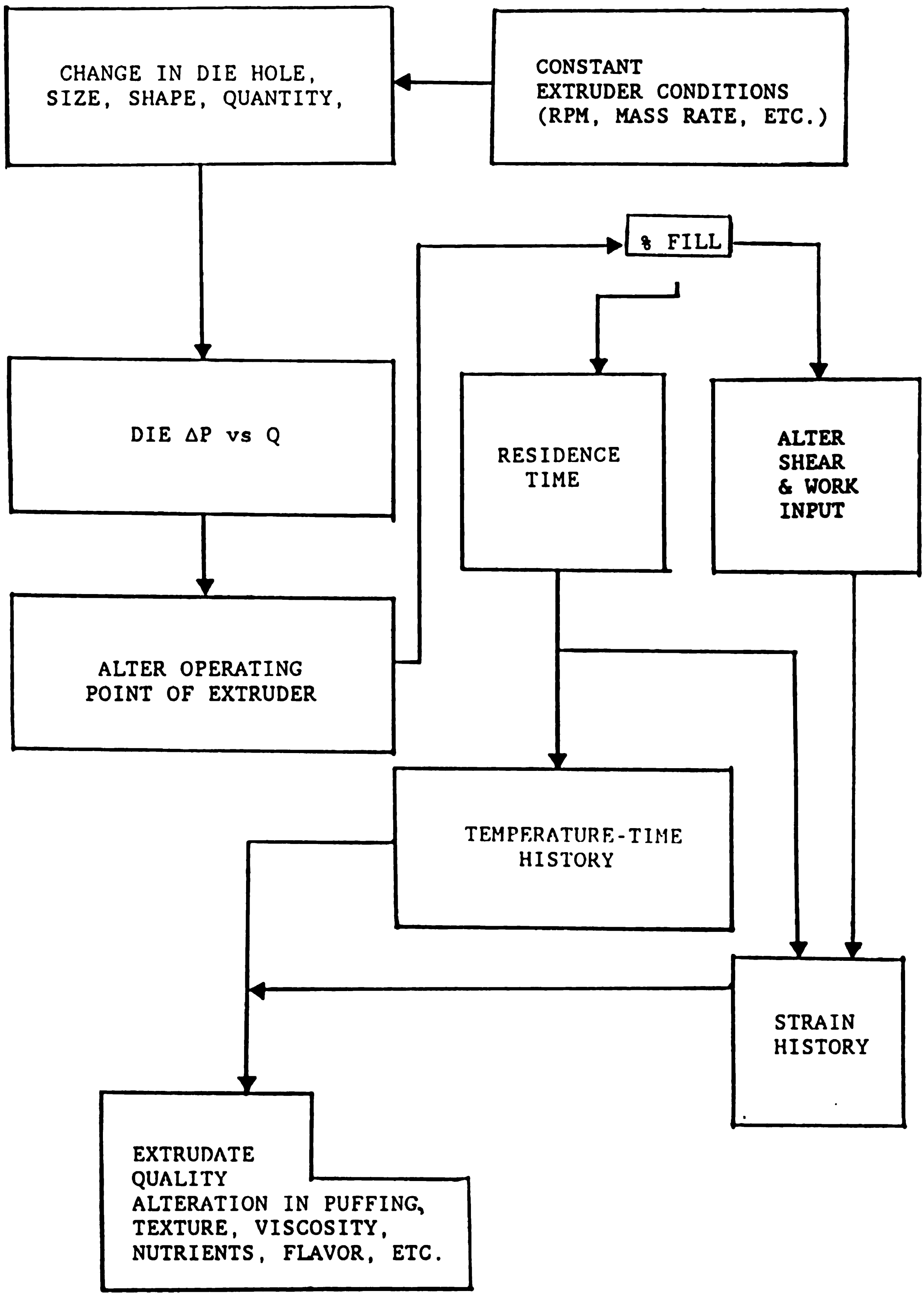


Figure 2. Schematic of effects of die change on extrusion parameters and extrudate quality.

Change in residence time directly affects process kinetics. Bigg and Middleman (1974) and Bruin et al. (1978) showed significant effects of die pressure drop on residence time for a single-screw extruder. Changes in residence time and power input change the temperature-time history, Ψ, and strain history, Φ. Changes in Ψ and Φ alter process kinetics, which change extrudate quality (Morgan, 1979; Dolan, 1986).

PRESSURE DROP MODELING

Pressure loss across extruder die assemblies can be separated into three components: entrance pressure drop, capillary (die hole) pressure drop, and exit pressure drop. Entrance pressure drop (ΔP_{ent}) consists of momentum losses due to changes in fluid velocity and flow direction, and energy required to overcome elastic forces. Exit pressure losses are due to the relaxation of elastic forces created during material contractions at the die entrance. Crater and Cuculo (1984) showed that ΔP_{ex} is less than 20% of ΔP_{ent} for high molecular weight polymers at shear rates of 100-2000 s^{-1}. Han and Kim (1971) showed ΔP_{ex} to be one to six percent of ΔP_{ent} for polyethylene in a shear rate range of 100-600s^{-1} with varying cone entry to capillary diameter contraction ratios. ΔP_{ex}'s of 10-30 percent of ΔP_{ent} were reported for high and low molecular weight polymers in a shear rate range of 100-1000 s^{-1} over various ranges of die entrance angles (Han, 1973). Assuming that elastic effects of food materials are orders of magnitude less than those for polymers, the author assumed $\Delta P_{ex} \ll \Delta P_{ent}$ for food extrusion dies and therefore can be neglected.

Entrance pressure drop cannot be neglected when assessing total pressure drop across most food extruder dies. Morgan (1979) demonstrated that ΔP_{ent} for soy dough represented 50 to 70 percent of total ΔP for capillary extrusion with the die L/D ranging from two to eight. ΔP_{ent} for soy dough ranged from 20 to 50 percent of total ΔP in a capillary extruder having L/D ratios of 20 to 80 (Remsen and Clark, 1978). Pena et al. (1981) showed ΔP_{ent} to be 83 percent of total ΔP for several polymers. From the above data it is concluded that entrance pressure drop is often the largest single component of total pressure drop. Die hole pressure drop was and assumed to account for the remainder of the total pressure drop.

Research has been conducted using finite element analysis to study capillary entrance pressure loss of polymers through single circular holes (Kim-E, 1983; Keunings and Crochet, 1984; Boger, 1982; Tanner et al., 1975; Mitsoulos et al., 1985). These models are limited to fixed contraction ratios and do not apply to multiple die holes. Other research has involved experimental data analysis of die entrance pressure loss through singular die holes (Crater and Cuculo, 1984; Jasberg et al., 1981; Ballenger et al., 1971; Jao and Chen, 1978; Morgan, 1979; Han et al., 1969; Han et al., 1970; Han and Kim, 1971; Han, 1973). These researchers did not develop a generalized model to relate entrance pressure to flow rate, material rheology and die geometry.

Boger (1982) developed the following model for predicting entrance loss through circular die geometries using non-elastic, non-Newtonian power law polymers:

$$\Delta P_{ent} = 2\tau_w \left[\frac{Re'}{32}(C' + 1) + n_c \right] \tag{1}$$

where Re′ is the generalized Reynold's number given as

$$Re' = \frac{\rho D^n V^{2-n}}{8^{n-1} m \left(\frac{3n+1}{4n}\right)^n} \tag{2}$$

and C′ and n'_c are coefficients based on the flow behavior index and are given in Table 1.

This model does not account for elasticity and has not been tested for food materials. However, it is the only model that the author found that could possibly be adapted to predict entrance pressure drop of food materials flowing through multiple die holes with irregular shapes. Hence, Boger's model is tested in this study for its applicability to foods, and it is compared to the model developed in this study.

Die hole pressure drop can be developed from simple momentum balances within a capillary. For Newtonian flow the Hagen-Poiseuille equation relates capillary pressure drop to flow rate, die length and radius (Bird et al., 1960). A similar development for non-Newtonian cases have been used by Shanoy and Saini (1985) and Michaeli (1984) for irregularly shaped die cross sections. Michaeli (1984) and Shanoy and Saini (1985) introduced factors to account for irregular cross sections. Shanoy and Saini (1985) also substituted the apparent viscosity of a Power law fluid in place of the Newtonian viscosity used in the Hagen-Pouiseuille equation.

Table 1. Coefficients for Boger (1982) entrance pressure drop model (Eqn. 1)

Flow Behavior Index n	Loss Coefficient C'	Couette Correction n'_c
1.0	1.33	0.59
0.9	1.25	0.70
0.8	1.17	0.85
0.7	1.08	1.01
0.6	0.97	1.15
0.5	0.85	1.34
0.4	0.7	1.53
0.3	0.53	1.76

CHAPTER III.

THEORETICAL DEVELOPMENT

PRESSURE DROP EQUATIONS

Total pressure loss across an extruder die hole can be expressed as

$$\Delta P_T = \Delta P_{ent} + \Delta P_{dhole} + \Delta P_{ex} \tag{3}$$

As discussed previously, exit pressure drop is assumed negligible for this study. The die hole pressure drop term of Eqn. (3) can be determined from transport phenomena equations of viscometric tube flow. For non-Newtonian non-elastic viscometric flow in the absence of slip, a force balance on a cylindrical element results in

$$\Delta P_{dhole} = \frac{2L}{R} \tau_w \tag{4}$$

For Newtonian tube flow, derivation of shear rate at the tube wall results in

$$\Gamma = \frac{4Q}{\pi R^3} \tag{5}$$

For a non-Newtonian fluid, true shear rate, γ, is given as a function of Γ as (Darby, 1976):

$$\gamma = \left(\frac{3n'+1}{4n'} \right) \Gamma \tag{6}$$

where n' is the Rabinowitsch correction factor (Whorlow, 1980) given as

$$n' = \frac{d \ln \tau_w}{d \ln \Gamma} \tag{7}$$

There are several models developed for describing rheological properties of non-Newtonian fluids. The most popular and simplest of these models for a shear thinning material is the Power-law model:

$$\tau_w = m \gamma^n \tag{8}$$

Harmann and Harper (1973) concluded that the Power-law model adequately describes the relationship, for a limited range of γ, for extruded cereal doughs. For a Power-law fluid, the Rabinowitsch correction factor $n' = n$. Hence, for circular die flow of a Power-law fluid, shear rate at the wall is described by

$$\gamma = \frac{3n+1}{4n} \left(\frac{4Q}{\pi R^3} \right) \tag{9}$$

substituting equations (5) and (6) into (4) and (8) yields an expression for die hole pressure loss as a function of rheological properties, size and flow rate for circular holes:

$$\Delta P_{dhole} = \frac{2\ L\ m}{\pi^n R^{3n+1}} \left(\frac{3n+1}{n} \right)^n (Q)^n \tag{10}$$

There is a need to reformulate Eqn. (10) for irregularly shaped conduits. However, solution of the equations of motion for irregularly shaped cross sections is complex and usually requires a numerical methods solution. Some authors have developed flow coefficients for specific geometries which are used to adjust the Hagen-Poiseuille equation for flow through irregular cross sections. Michaeli (1984) lists flow coefficients, f_p, for some cross sections of known aspect ratios, (height/width), and gives ΔP_{dhole} as

$$\Delta P_{dhole} = \frac{12\,\mu\,Q\,L}{BH^3}\;\frac{1}{f_p} \tag{11}$$

Irregular cross-sections without actual height and width dimensions such as hearts, moons, stars etc. are commonly used in food extrusion of snack foods and breakfast cereals. For this reason, it is essential that the die pressure drop model is not limited to dies of a given cross section or measurement of an aspect ratio.

Classical fluid dynamics makes use of the hydraulic radius, defined as:

$$r_h = \left(\frac{\text{Cross-Section of Flow Area}}{\text{Wetted Perimeter of Cross-section}} \right) \tag{12}$$

for evaluating pressure loss of turbulent Newtonian flow in irregularly shaped conduits (McCabe and Smith, 1976). Note that for a circular cross section, $r_h = R/2$. For laminar flow, use of the hydraulic radius without a flow coefficient is only an approximation (Michaeli, 1983; McCabe and Smith, 1976). However, combining the concept of the hydraulic radius with a flow coefficient might result in an effective solution of ΔP_{dhole} without requiring use of an aspect ratio. For non-Newtonian flow through irregular conduits, the following combination of equations (10),(11) and (12) is proposed:

$$\Delta P_{dhole} = \frac{L\,m}{(8\pi)^n r_h (3n+1)} \left[\frac{3n+1}{n} \right]^n Q^n \,\frac{1}{f_c} \tag{13}$$

where $2r_h$ has been substituted for R and the flow coefficient, f_c, has been adapted from f_p values of Michaeli (1984) and are listed in Figure 3 as a function of a shape factor, F. The shape factor is defined as the ratio of the diameter of the smallest circle (circle A, Figure 4) which totally encloses the die hole cross section to the diameter of the largest circle (circle B, Figure 4) which will fit completely inside the die hole cross section. Flow coefficients for other irregular shapes need to be developed but is beyond the scope of this study.

The entrance pressure drop term of Eqn. (3) is also a function of rheological properties as well as several die geometric variables. Table 2 lists variables which should be considered in determining die entrance losses for food materials. The die hole center spacing (s) is the distance between each hole on a concentric circle configuration as shown in Figure 5. The die inset angle (α) and the conduit entrance diameter, D_c, are defined in Figure 6.

No published literature was found for assessment of ΔP_{ent} for non-circular holes. For initial development, the author proposes that the shape factor, F, along with the hydraulic radius would be sufficient to describe the effect of noncircular cross-sections on entrance pressure.

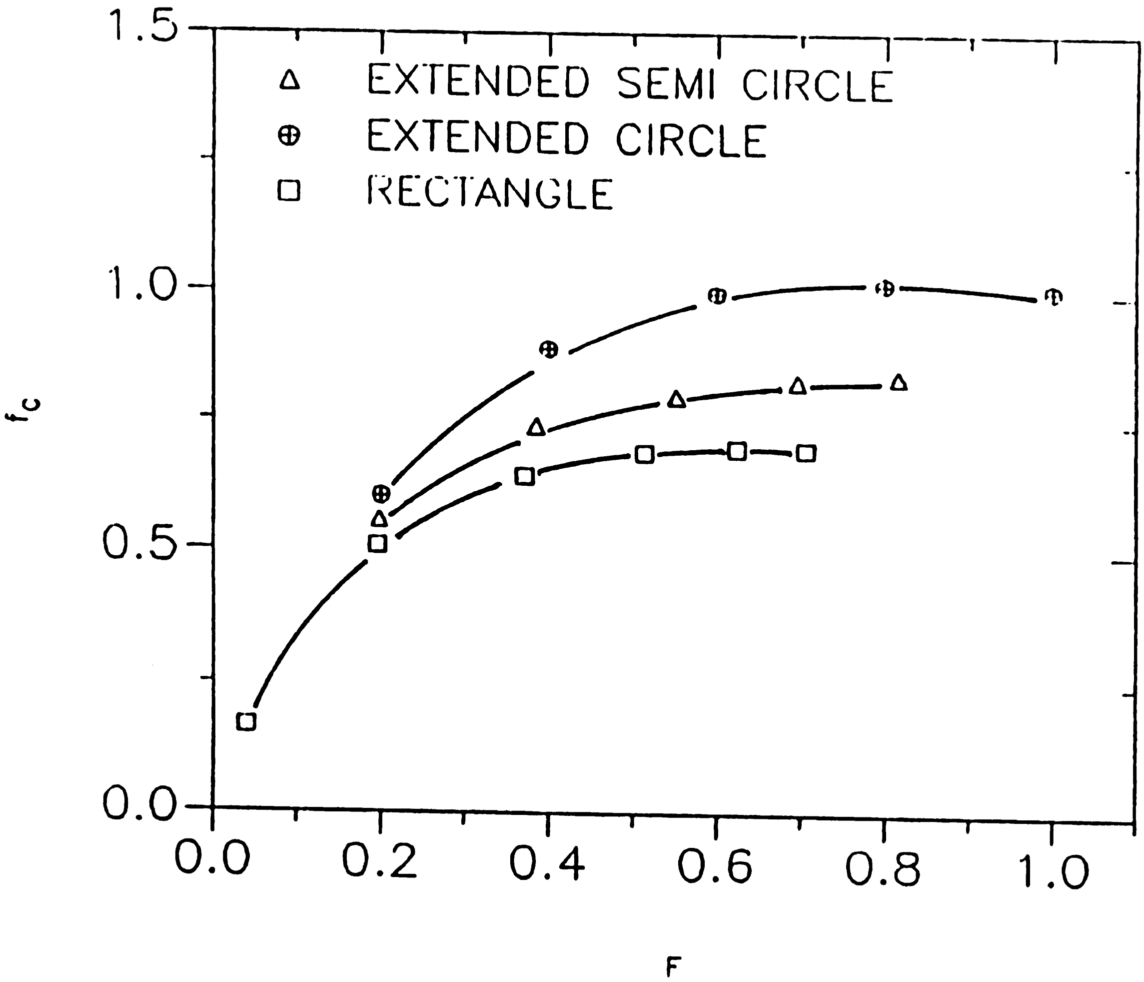


Figure 3. Flow coefficient, f_c, (from Michaeli, 1984) vs. shape factor, F, for non-Newtonian flow through irregular cross-sectioned die holes.

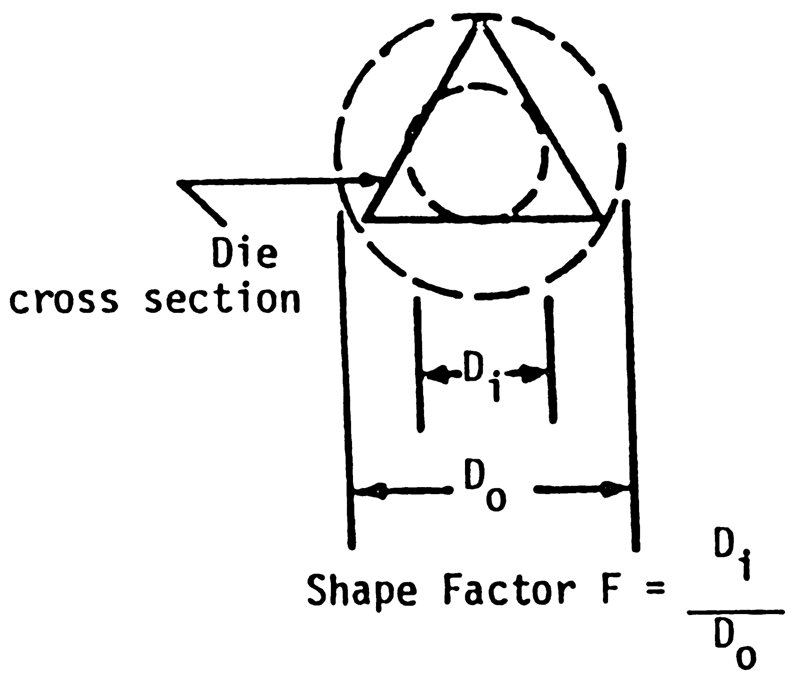


Figure 4. Definition of die hole shape factor, F.

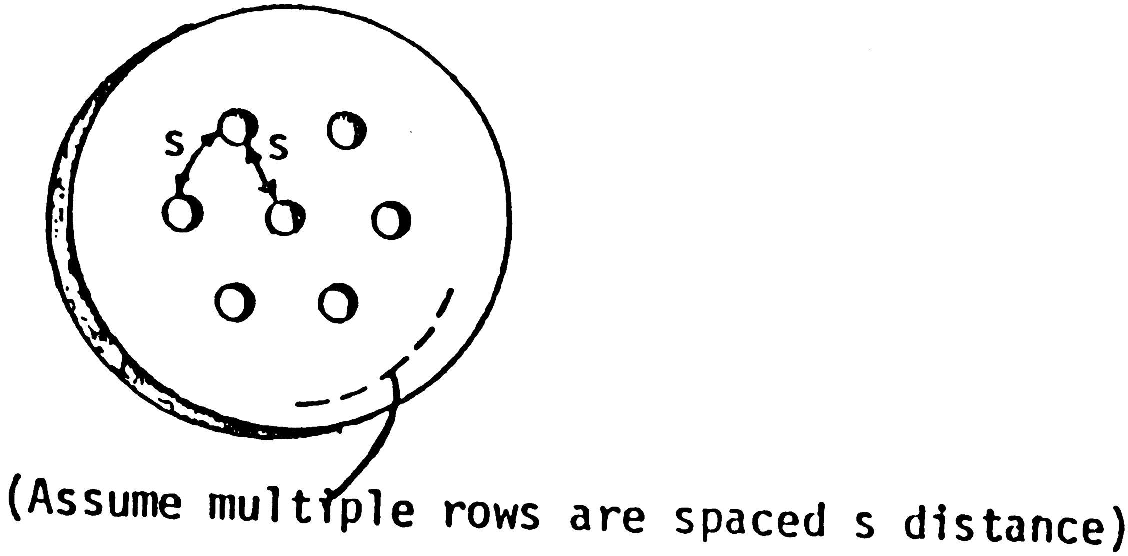


Figure 5. Definition of die hole spacing, s.

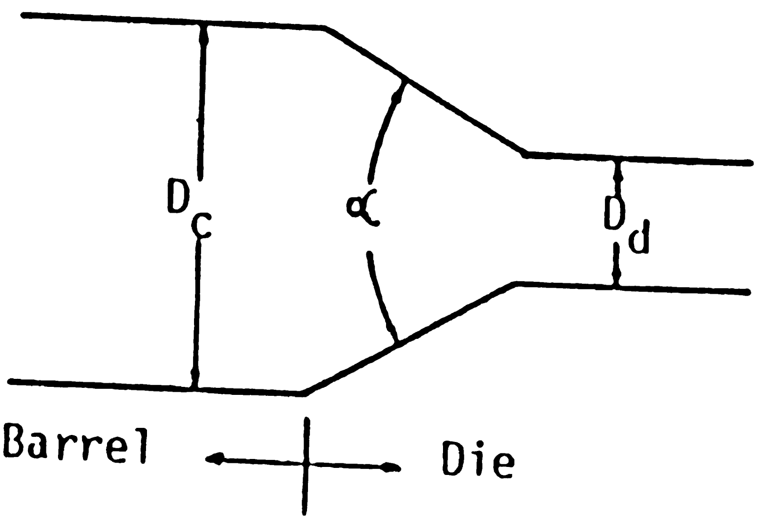


Figure 6. Definition of die entrance angle, α, and conduit entrance diameter, D_c.

Table 2. Variables affecting entrance pressure drop in food extruder dies

Process Variables	Notation	Dimensions
Entrance pressure loss of die assembly	ΔP_{ent}	$ML^{-1}t^{-2}$
Total volumetric flow rate	Q	L^3t^{-1}
Die Geometry		
# of die holes	n_d	---
Hydraulic radius of die holes	r_h	L
Shape factor of die holes	F	---
Diameter of upstream conduit at die entrance	D_c	L
Die hole center spacing	s	L
Die entrance angle	α	deg
Material Properties		
Shear thinning flow behavior index	n	---
Power law consistency coefficent	m	$ML^{-1}t^{2-n}$
Characteristic time constant	λ	t
Density of fluid at die entrance	ρ	ML^{-3}

ELASTICITY EQUATIONS

Little is understood about the influence of elastic properties of viscoelastic fluids on entry pressure drop (Boger, 1982). Some authors report that entrance losses for viscoelastic fluids may in fact be less than Newtonian cases (Black et al., 1975; Tanner, 1976; Yiriyayuthakorn and Caswell, 1980 (from Boger, 1982)).

Elastic fluids are generally characterized by the Weissenberg or Deborah numbers

$$We = \frac{\lambda\ v}{D} \qquad (14)$$

$$De = \frac{\lambda\ v}{L} \qquad (15)$$

The author elected to use the Weissenberg number as it is more commonly seen in published literature. The characteristic diameter, D, is assumed to be the die diameter.

Boger (1982) defines a characteristic time constant, λ by

$$\lambda = \frac{N_1}{2\ \tau_w\ \gamma} \qquad (16)$$

Huang and White (1980) used this equation in their investigation of the relationship between jet swell and the Weissenberg number. Eqn (16) is further reduced by relating N_1 to Γ. Analysis of plastic polymer data from Crater and Cuculo (1984) and White and Roman (1976) (Figure 7) shows that the primary normal stress difference (N_1) of some polymers can also be approximated by a power law function of the Newtonian shear rate as

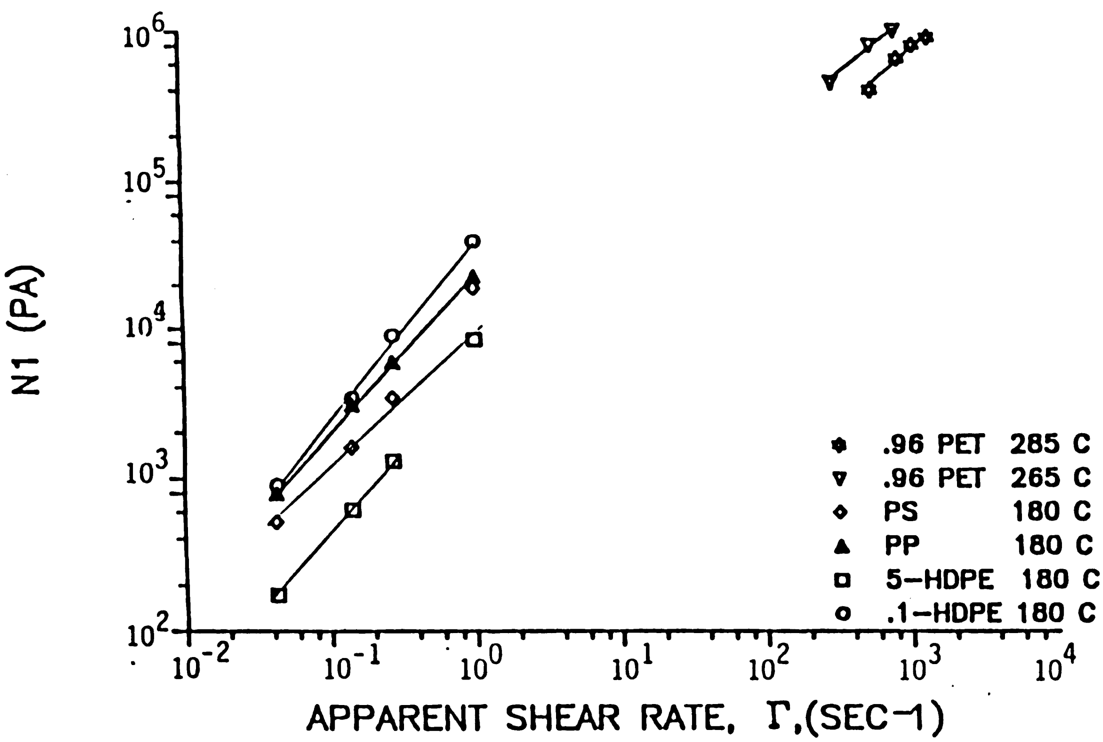


Figure 7. Primary normal stress difference (N_1) vs. shear rate data for various polymers studied by Crater and Cuculo (1984) and White and Roman (1976).

$$N_1 = K\,(\Gamma)^p \tag{17}$$

where p was found to range from 0.9 to 1.1. Values of K from data of White and Roman (1976) ranged from 10,000-30,000 Pa-sec^p for various polymers at 180 °C. Data from Crater and Cuculo (1984) yielded K values of 2000 and 5000 Pa-sec^p for polyethylene at temperatures of 285 °C and 265 °C, respectively, for shear rates of 200-2000 sec^{-1}. Substituting equations (6),(8),(9) and (17) into (16) gives

$$\lambda = \frac{K\left(\dfrac{Q}{2\pi r_h^{\,3}}\right)^{p-n-1}}{2m\left(\dfrac{3n+1}{4n}\right)^{n+1}} \tag{18}$$

Accurate measurement of N_1 vs. Γ data for extruded doughs is very difficult due to the presence of a yield stress and the need to simulate extrusion process conditions, e.g. temperature, shear rate and pressure, during measurement. For this reason a different method for estimating the time constant is suggested.

An alternative pseudo material time constant, λ_a, based on a treatise by Williams (1977), is defined as the first order time decay constant for jet swell (Figure 8). The λ_a is related to the jet swell ratio (β) and die residence time (t) by the following,

$$\beta = \beta_\infty + (\beta_o - \beta_\infty)\exp(-t/\lambda_a) \tag{19}$$

where β is the ratio of the instantaneous swell to the die diameter and β_o and β_∞ are the swell ratio at zero and infinite die lengths, respectively. β vs. residence time data are obtained by varying die L/D and measuring swell while holding Q and D constant.

Figure 8. Schematic of proposed method (Williams, 1977) for determining λ_a (at constant shear rate and hole diameter).

DIMENSIONAL ANALYSIS

Dimensional analysis was chosen for quantifying ΔP_{ent} because it most efficiently incorporates numerous parameters such as those listed in Table 2, and does not require solution of complex velocity profiles as would be necessary if the equations of motion were used. Astarita (1974) addresses theoretical limitations of using dimensional analysis to characterize flow of viscoelastic fluids when the same fluid is used for model and prototype scales. He implied that the only means by which all dimensional analysis criteria can be met is to use homologous non-Newtonian fluids, that is, two materials characterized by the same dimensionless operator of deformation histories but of unequal viscosity parameters.

The author elected to pursue a dimensional analysis approach despite the position presented by Astarita (1974) because this approach appears to be the only practical method for modeling die flow phenomena for food materials. Also, the relative elasticity of food materials is unknown. As previously mentioned, the elasticity of food materials is assumed to be much less than the elasticity of polymers and hence may not cause the significant error that Astarita (1974) found for highly elastic materials.

The desired relationship resulting from dimensional analysis of the parameters in Table 2 is

$$\Delta P_{ent} = f(Q,\ n_d,\ r_h,\ F,\ D_c,\ s,\ \alpha,\ m,\ n,\ \lambda,\ \rho) \qquad (20)$$

Eqn. (20) is reduced by the Buckingham Pi Theorem which states that the number of dimensionless and independent quantities required to express a relationship among the variables in any phenomena is equal to the number of quantities involved, minus the number of dimensions in which these quantities may be measured (Murphy, 1950). In this study there are three dimensions: length, mass and time. The resulting number of Pi terms developed from the variables of Table 2 is 9 (12-3).

Nine Π terms (Table 3) were derived to yield relationships considered meaningful in fluid mechanics. The π_1 term is based on the Euler number, the ratio of pressure forces to inertial forces. In this case, the pressure forces are entrance pressure forces.

The π_2 term is a simplified Reynold's number, the ratio of inertial forces to viscous forces. The Newtonian viscosity in the standard Reynold's number is replaced with the apparent viscosity of a Power law fluid evaluated at the wall. In place of the Power law model, another fluid model may be used to find an expression for the apparent viscosity in π_2.

The π_5 term is the Rabinowitsch correction factor and the π_6 term is the die contraction ratio. The π_8 term was based on the Weissenberg number and was defined to ensure a non-zero number (1.0) for inelastic fluids having a Weissenberg number at or near zero. Likewise π_9 was defined to be non-zero for single hole dies. π_3, π_4, π_7, and π_9 describe die geometry.

Assuming the Π terms are differentiable over the range of the variables considered, then the product solution method (Murphy, 1950) can be used to express π_1 as

$$\pi_1 = a\ (\pi_2)^{b_2}\ (\pi_3)^{b_3}\ (\pi_4)^{b_4}\ (\pi_5)^{b_5}\ (\pi_6)^{b_6}\ (\pi_7)^{b_7} (\pi_8)^{b_8}\ (\pi_9)^{b_9} \quad (21)$$

This form of the equation significantly reduces the number of experimental runs necessary to determine empirical constants. Independence of the Π terms is verified in Appendix A.

Table 3. List of Π terms

Π Term	Description
$\pi_1 = \frac{16\, n_d^2 r_h^4\, \Delta P_{ent}}{\rho\, Q^2}$	Entrance Euler number = ratio of entrance pressure forces to inertial forces (based on entrance pressure loss)
$\pi_2 = \frac{\rho\, Q}{\pi n_d r_h \bar{\eta}}$	Simplified Reynold's number analogous to Generalized Re

where

$$\bar{\eta}\,(\gamma = \gamma_{wall}) = m \left(\frac{Q}{2\pi n_d r_h^3}\right)^{n-1} \left(\frac{3n+1}{4n}\right)^{n-1}$$

for a Power law fluid.

Π Term	Description
$\pi_3 = n_d$	# holes in die head
$\pi_4 = F$	Shape Factor
$\pi_5 = (3n+1)/(4n)$	Rabinowitsch Correction Factor
$\pi_6 = \frac{16 n_d r_h^2}{D_c^2}$	Ratio of the total die hole area to the entry conduit area
$\pi_7 = \alpha$	Die entrance angle
$\pi_8 = 1 + \frac{\lambda\, Q}{16\pi\, n_d r_h^3}$	1 + Weissenberg number
$\pi_9 = s + 1$	Die hole center spacing

CHAPTER IV.

EXPERIMENTAL PROCEDURES

In order to verify the model, data from published literature were chosen to develop initial empirical constants, then experimental data were collected for various food materials and checked against the model. Data from six published sources (Table 4) were chosen for initial development. Published data for ΔP_{ent} vs. Q were mainly from the plastics industry and did not incorporate effects for irregular shapes nor multiple die holes. Therefore, experimental data were also collected to develop empirical constants for food materials flowing through irregularly shaped and multiple die holes.

EXPERIMENTAL DESIGN

A Baker Perkins 50mm twin-screw extruder (TSE) and an Instron (model #4202) capillary rheometer (CR) were used to conduct extrusion die experiments. The TSE was chosen because of its increasing popularity in the food industry. In addition, due to the fact that the TSE is pilot plant size, data collected on this machine should give model parameters which can be realistically used in the food industry. Also, as the extruder is a twin-screw, its operating point is less altered by die changes than for a single-screw extruder. It is important that the same food product be delivered to all dies in order to measure effects of the various die changes without the compounding effects of varying rheological properties.

TABLE 4. Data from Literature Sources (Raw Data given in Appendix Q)

Material Tested	Author(s)	Shear rate range (sec^{-1})
.72 PE Terephthalate at 285°C	Crater and Cuculo (1984)	150-1250
.72 PE Terephthalate at 265°C	Crater and Cuculo (1984)	150-1250
.96 PE Terephthalate at 285°C	Crater and Cuculo (1984)	300-1600
.96 PE Terephthalate at 265°C	Crater and Cuculo (1984)	100-1000
Polyethylene (PE)	Jasberg et al. (1981)	200-5000
HDPE(1)	Han (1973)	100-600
LDPE(2)	Han (1973)	100-800
Soy Dough 32% MC. 50 °C	Remsen and Clark (1978)	3-150
Soy Dough 30% MC. 120 °C	Jasberg et al. (1981)	100-3000
Soy Dough 34% MC. 24 °C	Morgan (1979)	1-19
Soy Dough 35% MC. 160 °C	Morgan (1979)	47-950

(1) High density polyethylene

(2) Low density polyethylene

The CR was selected because of its ability to maintain constant temperature. Data collected with the CR can be used to model effects of moisture content,temperature, shear rate and thermal kinetics as shown by Morgan (1979) and Mackey et al. (1987). However, the CR is limited to the case of single hole dies and zero shear history. Hence, data from the TSE and CR compliment each other well. Rheological properties were changed by varying shear rate, moisture content, extrusion temperature and thermal history.

Three materials (soy polysaccharide (SPS), potato dough and defatted soy dough.) were selected for experimental tests to verify the model for a wide range of food materials. Criteria of the test materials were that one be a starch based dough, one a protein based dough, and another a food type dough which does not undergo significant physicochemical changes during extrusion. Potato flour, defatted soy flour and soy polysaccharide (SPS) were chosen to meet these criteria, respectively. Potato flour (Lamb-Weston Company Portland, OR) was chosen as the starch based material because it was pregelatinized and hence would not significantly undergo further gelatinization during experimentation (Mackey et al., 1987). Pregelatinization of the starch dough was desired in order that the rheological properties of the dough would not have to be adjusted for gelatinization effects. Defatted soy flour was selected because denaturation effects of this dough occurred only above 70°C and could be adjusted for by a model developed by Morgan (1979). Soyafluff 200w soy flour from Central Soya (Ft. Wayne, IN), was used for preparing soy doughs. Soy polysaccharide (SPS) was chosen as an inert type food substance as it shows no significant kinetic effects due to gelatinization or denaturation under normal extrusion conditions. SPS was donated by the Protein Technology Division of the Ralston Purina Company (St. Louis, MO).

Tables 5 and 6 outline the experimental design used in this study. Two duplications of tests on SPS were conducted on the capillary rheometer and TSE. Spot check replications were made for potato flour on the TSE at the same RPM and most tests were duplicated at two different RPMs. Defatted soy flour was held at a constant pressure for a minimum of three to four minutes before measurements were recorded.

TABLE 5. Experimental design for capillary rheometer

<u>Soy polysaccharide</u>

Temperature of capillary Rheometer (°C)	Crosshead Speed (1) (mm/min)	Die Diameter (2) (cm)	Die Length (cm)	Moisture Content (%)
25	100,300,500	0.15875 0.3175	0.8,5.0 5.2	60
25,50,70	100,300,500	0.15875 0.3175	0.8,5.0 5.2	50,70

(1) $2 < \Gamma < 1500\ s^{-1}$
(2) $2 < L/D < 35$

TABLE 6. Experimental design for twin screw-extruder

INGREDIENT	DIE(1)	BARREL TEMP (^oC)	SCREW SPEED (rpm)	FLOW RATE (kg/hr)	MOISTURE CONTENT (% wet basis)	REPS
DEFATTED SOY DOUGH	Q:L,S 8TH:L,S	155	150 280,350	31.8,49.9, 68.1	56	2
	Q:L,S 8TH:L,S	55,200	280	31.8,49.9 68.1	56	2
	Q:M 8TH:M	155	280	31.8,49.9 68.1	56	2
POTATO DOUGH	RECT. Q:L,S 8TH:L,S 3H:L,S FF:L,S	12.8	100,300	31.8,49.9 68.1	50	1
SPS DOUGH	Q:M,S 8TH:L,S 3H:L,S FF:L,S RECT:L,S 21H:S 3 SLIT: S	12.8	350	31.8,49.9 68.1	64.8	2
	Q:M,S 8TH:L,S 3H:L,S FF:L,S RECT:L,S 21H:S 3 SLIT: S	12.8	240	31.8,49.9 68.1	58.6	2

(1) Die notation and dimensions given in Table 7.

CAPILLARY RHEOMETER PROCEDURES

The capillary rheometer was used to collect data for determining viscosity as a function of temperature. The viscosity-temperature relationship is needed to adjust twin-screw extruder data to an average die temperature for each material. Capillary rheometry was performed on SPS; previous data for defatted soy dough and potato dough had been collected and analyzed by Morgan (1978) and Mackey et al. (1986) respectively.

The CR was preheated to a constant barrel temperature for approximately 30 to 60 minutes before testing. Tests were conducted by rapidly loading the CR by dropping twin-screw extruded SPS strips into the CR barrel and tamping with a ramrod until the barrel was full. The sample was then compressed at 500 mm/min with the plunger until extrudate appeared at the die (Figure 9). As soon as product began to exit the die, the plunger was immediately stopped, and the heating time began. Time required for sample loading and precompression was typically 30-60 seconds. Morgan (1979) estimated that a two minute heating time after the material was precompressed was required to bring the material center temperature to within one degree celcius of the wall temperature. After the two minute heating time was reached, the sample was then extruded at a constant plunger velocity. Three constant plunger velocities were used per sample loading, (500, 300, and 100 mm/min) thus giving a range of shear rates. A ten KN Instron cross-head load cell measured the plunger force as a function of time, recorded by an XY chart recorder. The resulting force-velocity (F_{xh} - V_{xh}) data could then be converted to ΔP vs. Q and τ_w vs. Γ data using the CR barrel and die dimensions (Appendix C).

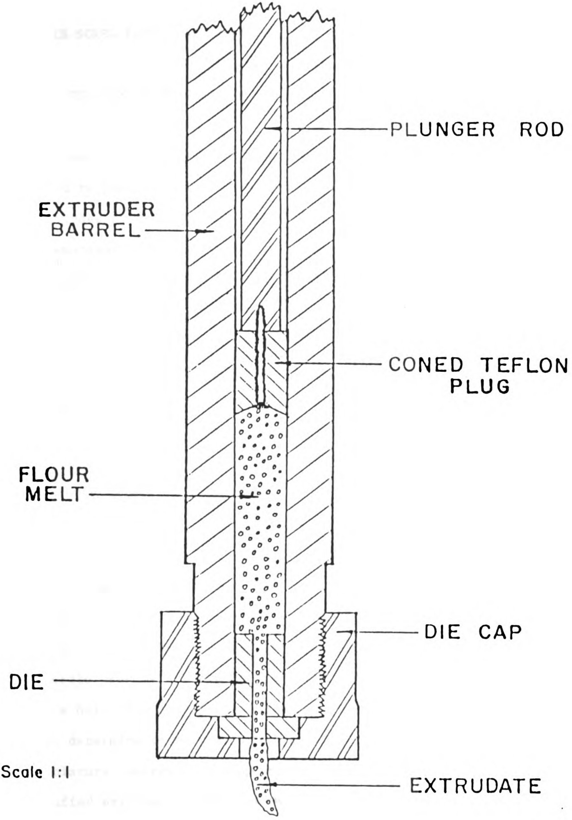


Figure 9. Illustration of capillary extrusion process.

TWIN SCREW EXTRUSION PROCEDURES

TSE SAMPLE PREPARATION

As the TSE is an excellent mixer of solids and liquids, there was no need to pre-mix the test doughs. Flour was metered directly into the extruder by means of a K-Tron feeder and water was injected at a downstream distance of one L/D from the dry feed port. The water injection pump and K-Tron feeder were calibrated to determine water injection rate and flour feed rate at given set points of the pump and feeder respectively, and the resulting calibrations were used to preselect moisture content for a given product rate. A calibration program for determining moisture content and product rate given feeder and injection pump set points is given in Appendix D.

TSE EXTRUSION TECHNIQUES

Brass extruder dies (Table 7) were mounted in pairs in a Baker Perkins twin hole die head. Die temperature was recorded with an Omega digital thermometer (model HH-70TF) with a veterinarian hypodermic needle used as a thermocouple probe The probe was inserted through a die hole to a specified distance. Preliminary extrusion runs were made to determine screw configurations, barrel temperatures and product moisture contents which gave a motor load of less than 70% and a non-puffed extrudate. The non-puffing criterion was specified to ensure that there was no flashing inside the extruder die, because the flashing may cause significant end effect errors. Screw configurations for each test material are listed in Table 8.

TABLE 7. Twin-screw extruder die dimensions(1)

DIE NOTATION	ENTRANCE ANGLE (degrees)	LENGTH (cm)	DIAMETER (cm)	NUMBER OF HOLES
Q:L(2)	90	5.16	0.635	1
Q:M	90	2.625	0.635	1
Q:S	90	.642	0.635	1
8TH:L	90	2.6	0.3175	1
8TH:M	90	1.245	0.3175	1
8TH:S	90	0.4	0.3175	1
FF:L	90	2.67	0.3175	1
FF:S	90	.405	0.3175	1
3H:L	90	2.58	0.3175	3
3H:S	90	0.37	0.3175	3
RECT:L	180	3.18	.625x.318	1
RECT:S	180	0.2	.625x.318	1

(1) Dimensions per die. Dies were mounted in pairs.
(2) The shorthand die notation names signify the following:

Q: large circular diameter
8th: narrow circular diameter
FF: full flange entry die
3H: three hole die
RECT: rectangular cross section
L: Long die length
M: Medium die length
S: Short die lengths

Figures of cross sections for dies without 180 degree entrance angle are given in appendix B.

Table 8. Screw configurations of MPF-50D/25 Baker-Perkins twin-screw extruder.

MATERIAL:	POTATO		DEFATTED SOY		SPS	
EXTRUDER L/D:	15		15		15	
SCREW CONFIGURATION						
	LENGTH (cm)	SCREW TYPE	LENGTH (cm)	SCREW TYPE	LENGTH (cm)	SCREW TYPE
	17.78	FS	17.78	FS	20.32	FS
	7.62	30F	7.62	30F	6.35	30F
	7.62	FS	7.62	FS	5.08	FS
	5.08	30F	5.08	30F	3.81	30F
	2.54	45F	5.08	FS	7.62	FS
	5.08	FS	3.81	30F	3.81	30F
	6.35	30F	8.89	30F	5.08	FS
	5.08	FS	27.94	FS	5.08	30F
	5.08	30F			17.78	SL
	12.7	SL				

NOTATION
FS - Feed Screw
30F - 30 degrees Forwarding Paddles
45F - 45 degrees Forwarding Paddles
SL - Single Lead screws

Different extrusion techniques were used for each material. Potato flour was extruded at various RPMs to determine effects of work input on extrudate properties. Water was injected by means of a Bran & Lubbe injection pump (type w-p33) and pressure was measured with a Gentran 0-3000 PSI (0-20684 KPa) transducer (model# GT75K-3M) and recorded with a Gentran digital readout. Temperature was measured by holding the thermocouple probe through the die holes at a distance of 2.54 cm from the extruder screw tips. Product rates were altered for each die while the die was in place. The extruder was shut down while dies were changed.

SPS was extruded at a low RPM to decrease work input and temperature of the material. Water was injected with a Cole Parmer parastolic pump (model# 7015) attached to a variable speed motor. Pressure was recorded with the Gentran transducer and digital readout.

Temperature was recorded in the same manner as during potato dough extrusion. Product rates for a given calibrated moisture content were altered for each die and only the flour feeder was shut off while the dies were changed. Experiments for each die were repeated at each calibrated moisture content.

Defatted soy flour was extruded at a low RPM to decrease work input and temperature, yet at a high enough RPM to ensure the flour would not back up in the feed hopper. Water was injected with the Bran & Lubbe Pump. Temperature was recorded by inserting the thermocouple probe to the die entrance, and pressure was measured with a Dynisco 0-500 PSI (0-3447 KPa) transducer (model# PT415-5C-6) and recorded with an Omega strip chart recorder (model# RD2020). The product rate was held constant and pressure measurements were made on all dies before the product rate was changed. During die changes the feeder was shut off long enough to remove the die head bolts, then immediately turned back on. The die head was remounted with the extruder operating at calibrated production rate.

MOISTURE CONTENT ANALYSIS

All moisture contents were determined by oven drying the material at 100°C for 24 hours (ASAE std. S358). Samples of material were placed in small aluminum weighing dishes and dried in a Central Scientific Co. oven (Cat. # 95100 A). Three moisture checks were taken on the CR samples and one on the TSE samples. However, as the extruder was operated at the same calibrated moisture content for several dies, several TSE samples of the same calibrated moisture content were actually taken.

DATA ANALYSIS

Flow through the extruder die was assumed to be viscometric capillary flow (steady axial laminar flow of an incompressible fluid) and ΔP vs. Q data were analyzed by the procedures outlined by Darby (1976) to obtain ΔP_{ent} and τ_w vs. γ data. Eqn. 4 can be rearranged as

$$\tau_w = \frac{\Delta P_{dhole} R}{2 L} \qquad (22)$$

Where ΔP_{dhole} is expressed as ΔP_T minus ΔP_{ent}. For noncircular holes, shear stress was assumed to be the same as τ_w for circular holes for the same extrusion conditions. τ_w was not calculated for noncircular holes as it is a function of radius, and the relationship between τ_w and hydraulic radius requires further study before accurate computation for noncircular holes can be made.

ΔP_T was measured for all experimental data. ΔP_{ent} was determined by Bagley's technique (Bagley, 1957), by conducting extrusion tests with dies of the same diameter but different lengths and plotting the values of ΔP_T vs. L/D of the die for constant Γ. For fully developed non-slip flow, ΔP_T is linearly related to die L/D with end effects pressure drop, ΔP_e, being the intercept at L/D = 0 (Figure 10). End effects pressure drop is a combination of entrance and exit pressure drop but, as previously discussed, exit pressure drop is assumed to be negligible compared to entrance pressure drop. To ensure accurate measurement of ΔP_{ent}, dies were chosen to be as short as possible to decrease the extrapolation distance, yet long enough such that flow was fully developed within the die. Collins and Schowalter (1963) give a prediction for entrance length vs. flow behavior index, n, for circular contractions (Figure 11). For low Reynold's numbers (less than one)

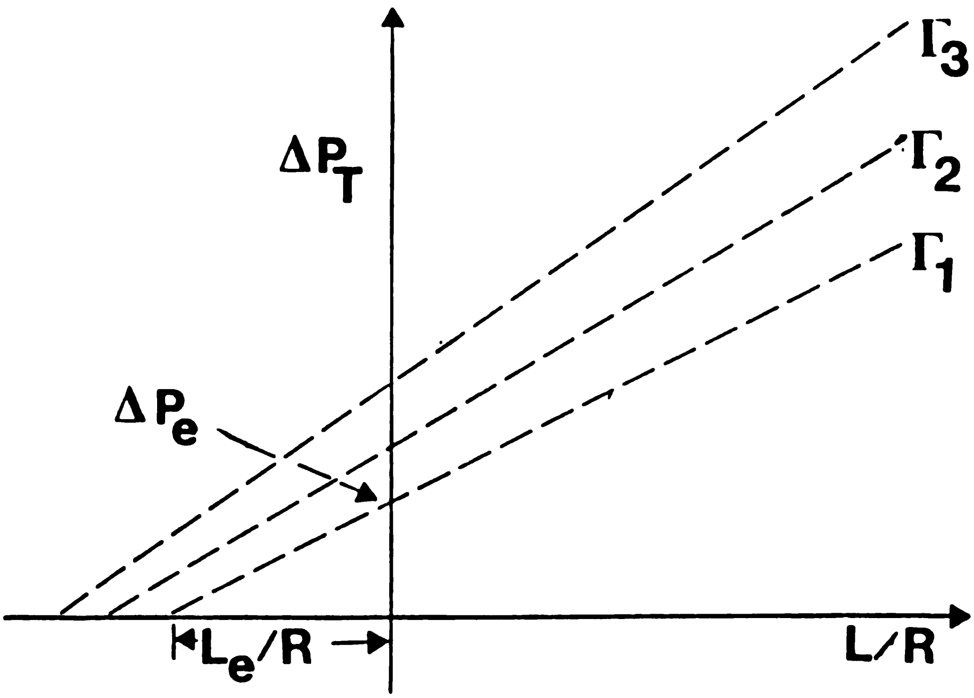


Figure 10. Schematic of end effects for ΔP_T vs. Γ through dies of same diameter, different lengths. ΔP_e and L_e/R correspond to the y-intercept and x-intercept of each shear rate line respectively ($\Gamma_3 > \Gamma_2 > \Gamma_1$).

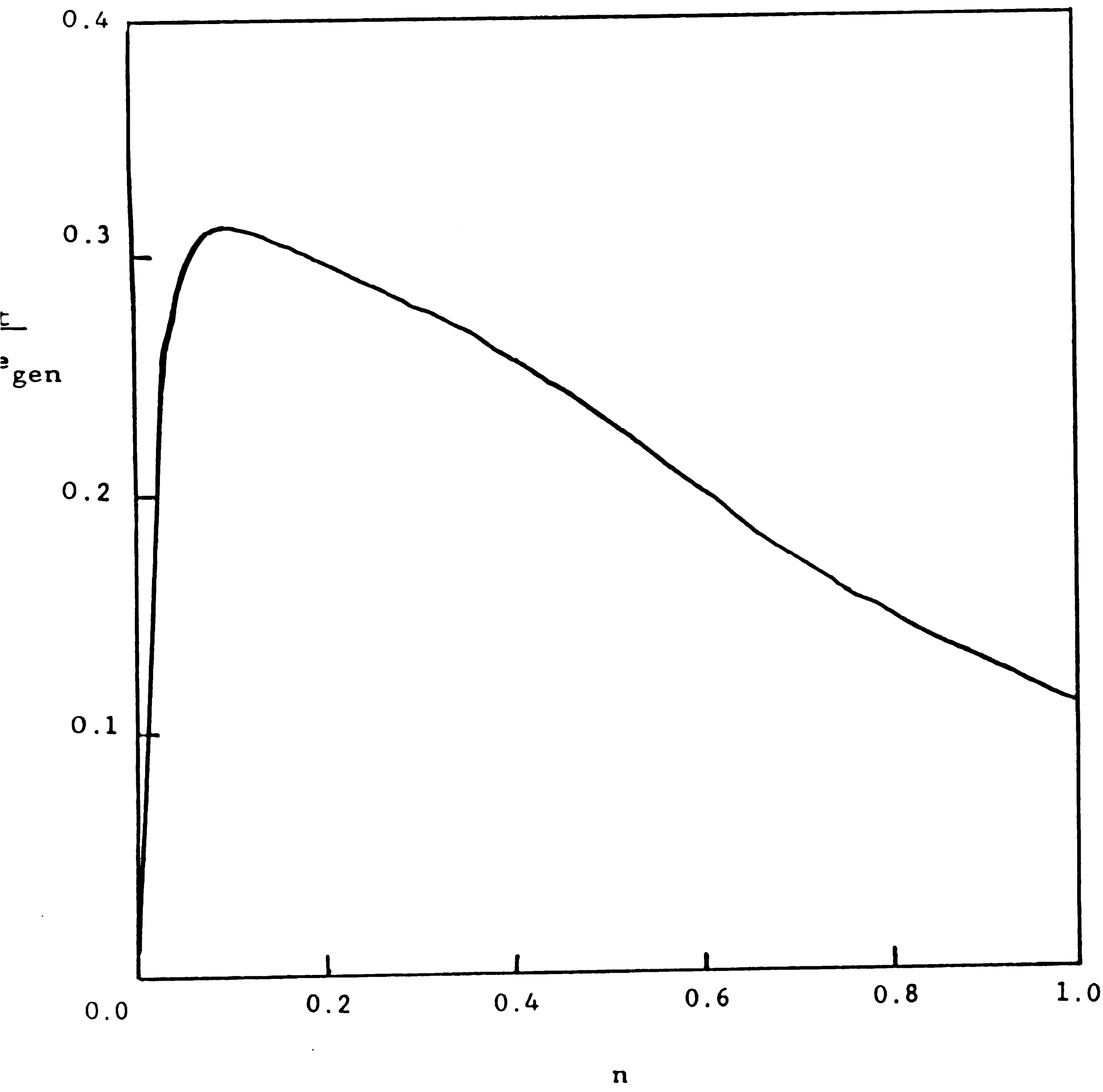


Figure 11. Relationship of entry length and Power law index (Analysis by Collins and Schowalter (1963)).

as occur in food extruder dies, L/D of one is well within the fully developed region. Measurement of the jet swell ratio, β', for assessing the elastic time constant (Eqn. 19) was conducted by use of close-up photography using three dies of constant diameter but different lengths.

SLIP

An error which may occur during the measurement of rheological properties in an extruder die is slip, which is a non-zero velocity of material at the die wall. This is a sliding surface phenomenon. All previous development assumes a zero velocity at the capillary wall. The presence of slip causes an error in measuring Γ. As die ΔP vs. Γ data are directly related to τ_w vs. γ, the error in Γ induced by slip would translate into erroneous rheological data. Other authors have found the occurance of slip prevalent in their research on single screw extrusion of polymer melts (Worth and Parnaby, 1977; Mennig, 1976). Methods for analyzing for slip are given in Appendix E.

GENERALIZED VISCOSITY MODELS

During TSE extrusion, changes in die geometry induces changes in thermal and shear history and hence protein denaturation and/or starch gelatinization. This in turn directly affects material viscosity at the die. All data analysis methods presented in this study assume constant viscosity from die to die. Hence, a technique is needed to account for changes in die viscosity due to variation in die temperature and TSE process histories. This was accomplished by the use of a generalized viscosity model similar to that presented by Morgan et al. (1987) for defatted soy flour. The model by Morgan et al. (1987) predicts apparent viscosity as a function of moisture content, shear rate, temperature and an integral temperature-time history defined as

$$\Psi(T,t) = \int_0^t T(t)\, e^{\Delta E/RT(t)}\, dt; \quad \Psi\,(T(t) < T_{th}) = 0 \tag{23}$$

where the threshhold temperature is 70°C (denaturation temperature for protein). Morgan et al. (1987) developed a generalized viscosity model based the Heinz Casson flow model. Adapting the flow model to a Power law fluid model yields:

$$\eta(\gamma,T,MC,\Psi) =$$

$$\phi e^{\frac{\Delta Ev}{R}[T^{-1}-T_R^{-1}]+b[MC-MC_R]}\, m\gamma^{n-1}\, [1 + \beta_2(1-MC)^{\alpha}(1-e^{-k\,\Psi(T,t)})^{\alpha}] \tag{24}$$

Bagley's technique of determining entrance pressure assumes constant viscosity of material for all die lengths. The generalized viscosity model used to adjust die pressure for changes in viscosity due to temperature and moisture effects is:

$$\Delta P_{adj} = \Delta P_{obs} e^{\frac{\Delta Ev}{R}[T^{-1}+T_R^{-1}]+b[MC-MC_R]} \tag{25}$$

Eqn. (25) assumes extrusion temperatures below the denaturation threshhold temperature for protein doughs and neglects any viscosity changes due to gelatinization of starch doughs.

Because of lack of available information on shear history effects on viscosity of extruded protein or starch doughs, no attempt was made to adjust ΔP data for variations in shear history within the TSE. However, work input to the material was calculated for each test as:

$$W.I. = 0.00336 \times \frac{\%\ Tq \times RPM}{\dot{M}} \quad (kw\text{-}hr/kg) \qquad (26)$$

for a Baker Perkins 50mm twin screw extruder where % Tq is the percent of maximum full load torque.

DATA ANALYSIS TECHNIQUES

Because of the difficulties maintaining a constant extrudate viscosity from the TSE extruder, a large amount of error in its measurement is expected. Much error is due to the difficulty of measuring die temperature accurately, and inaccurate pressure recordings due to slip in the die. In order to reduce effects of error, a standard was determined for objectively screening data for analysis. The coefficient of variance was chosen for this standard even though only two or three replications of each point were taken. Since there are no statistical guidelines for this method, the coefficient of variance was used strictly as an arbitrary standard with no statistical significance. All pressure data replications with a coefficient of variance greater than 20 percent after adjusting for temperature were excluded from analysis. Also, all data with a coefficient of variance of greater than 20 percent for τ_w calculated from long and short dies were excluded from the analysis. Data with τ_w at highest Γ lower than the τ_w at the lowest Γ were excluded from the analysis.

Rheological properties of all data were determined by SAS analysis (SAS, version 5). SAS programs for analyzing data for the CR and the TSE are listed in appendices F and G respectively.

CHAPTER V.

RESULTS AND DISCUSSION

EXPERIMENTAL DATA

RHEOLOGICAL PARAMETERS OF CAPILLARY RHEOMETER DATA

Rheological properties including a temperature correction factor were determined by using the capillary rheometer. Plunger force at the die, F_{xh}, vs cross-head velocity, V_{xh} data for SPS are given in Appendix H. Calculated τ_w vs. Γ values for SPS at given moisture contents and temperatures are given in Appendix I. For a constant moisture content and temperature, data from the 0.15875 cm and 0.3175 cm diameter dies were combined to give a wide range of shear rates. Plots of τ_w vs. Γ for 50% and 60% MC are given in Figures 12 and 13 respectively. As the shear stress data for both die diameters overlayed each other well, it was assumed that slip was insignificant.

The Power-law consistency coefficient, m, and the flow behavior index, n, were computed from Appendix I data assuming that over a small range of moisture content and temperature, n is not a function of moisture content or temperature (Harper, 1981). Values for computed m and n from the 50% and 60% MC SPS data are given in Table 9. Variation in n was insignificant and hence an average n value was used. CR data for the 70% MC SPS had significant scatter and hence, calculation of m and n values from the data were not made.

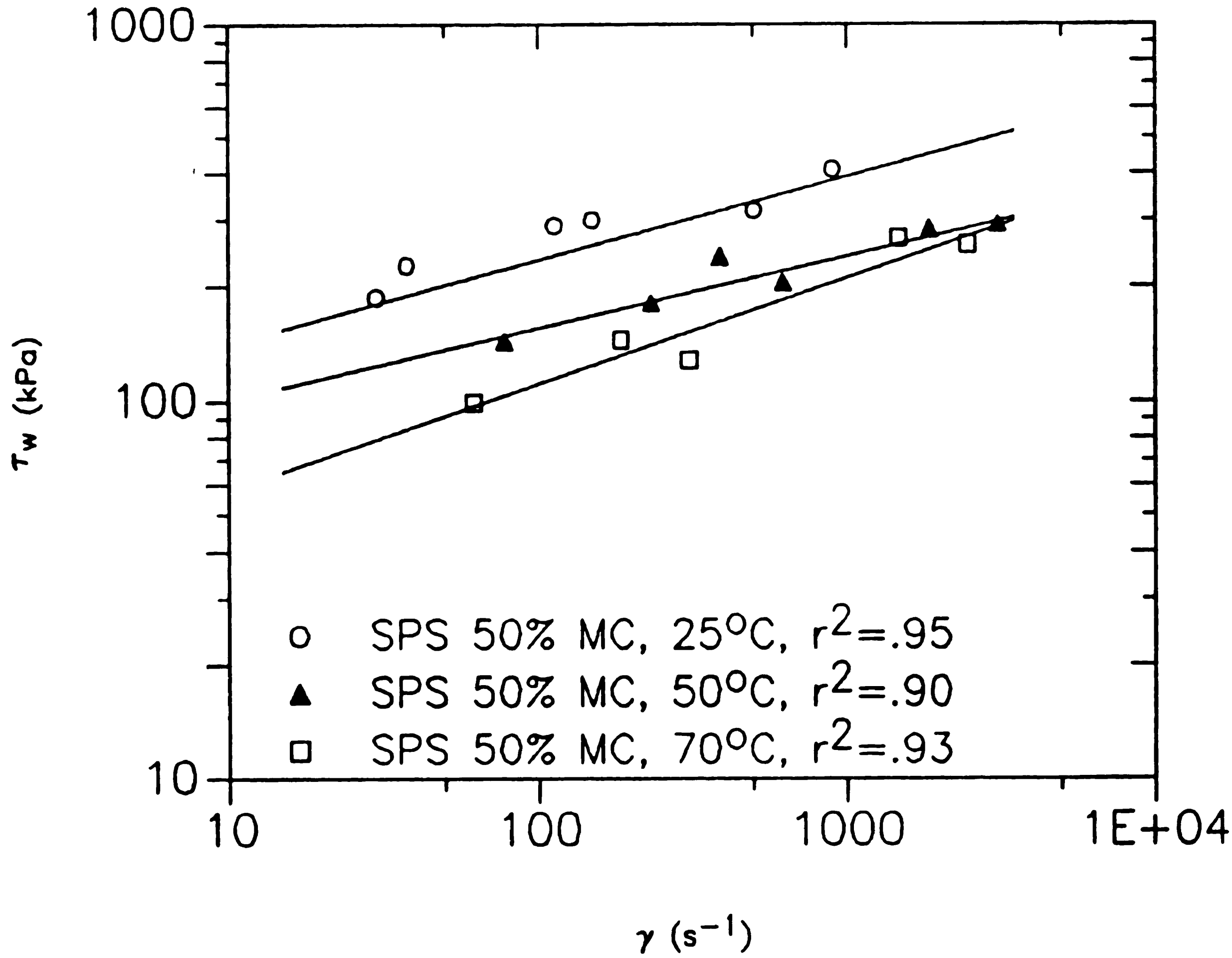


Figure 12. Shear stress vs. shear rate for SPS extruded with a capillary rheometer (data points are means of four observations).

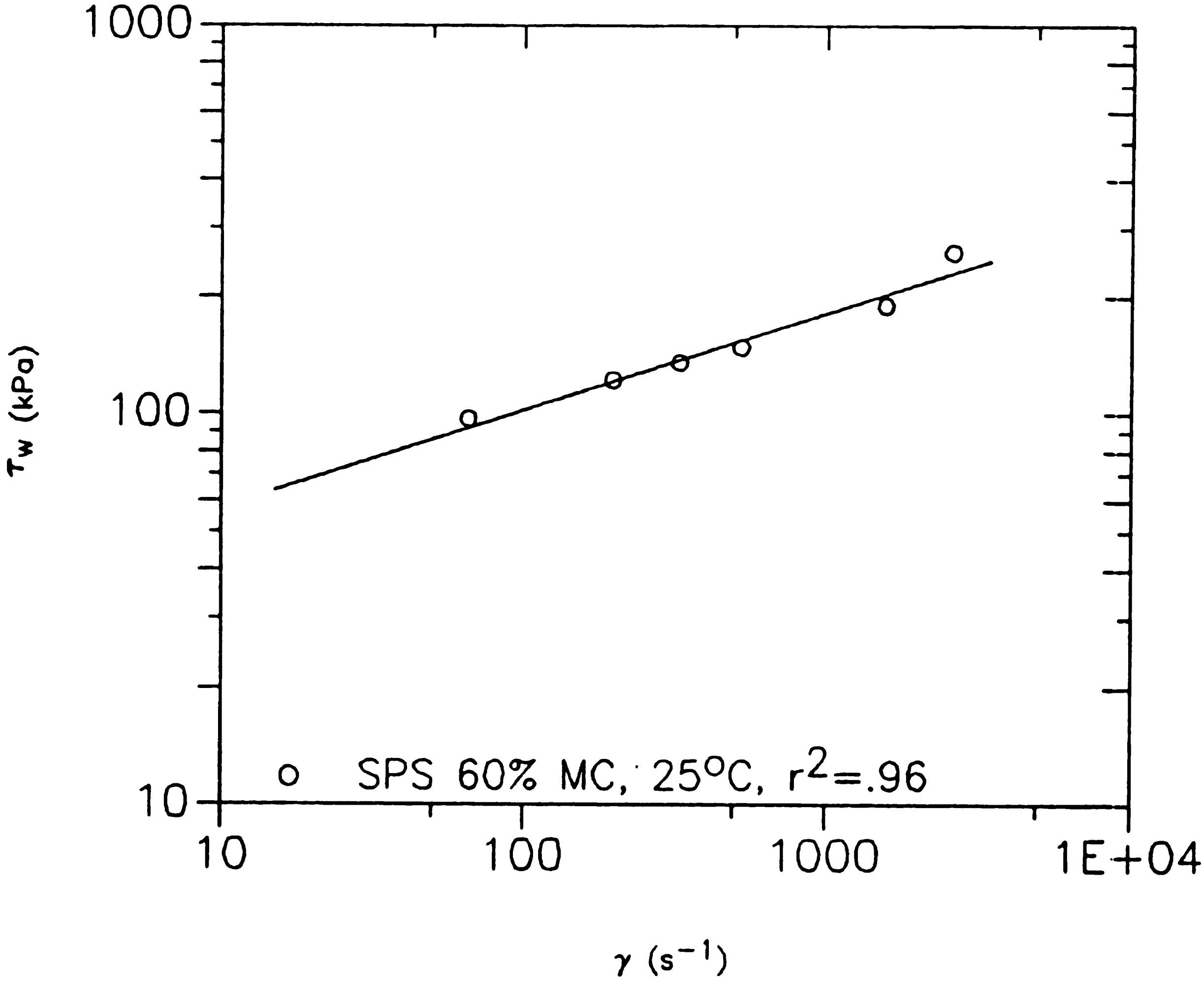


Figure 13. Shear stress vs. shear rate for SPS extruded with a capillary rheometer (Data points are means of four observations).

Table 9. Power law parameters for SPS determined by using a capillary rheometer

MC (%)	TEMP (^oC)	m (KPa)	n	r^2
50	25	86	.22	0.95
50	50	64.4	.19	0.90
50	70	30.4	.28	0.93
60	25	32.2	.25	0.96

The activation energy, E_v, was computed to be 4520 cal/gmol which compares to E_v values of 4500-8500 cal/gmol for food materials (Harper, 1981). A plot of log m vs 1/T is given in Figure 14. No moisture correction term was calculated as not enough data were available, and this term was not needed for correcting extrusion data. Resulting general viscosity parameters (Eqn. 24) are given in Table 10 along with those given by Mackey et al. (1987) for potato flour, and Morgan et al. (1987) for defatted soy flour. A plot of log η vs. 1/T for shear rate of 100 sec^{-1} for potato flour is given in Figure 15. The observed data points for η vs. 1/T (Figure 15) were used for adjusting the TSE potato data for temperature using Eqn. 25.

Table 10. Rheological properties of extruded materials determined by using a capillary rheometer

Matl	MC_{ref} (%)	T_{ref} (^oC)	m (KPa)	n	r^2	E_v (cal/gmol)	b
SPS	50.0	50	64.4	.23	.9	4520	--
PF(1)	35.0	60	34.9	.25	--	8729	-8.63
DSF(2)	34.0	68	8.58	.5	--	6800	-21

(1) Potato Dough (Mackey et al., 1987)
(2) Defatted soy dough (Morgan et al., 1987), Power law approximation

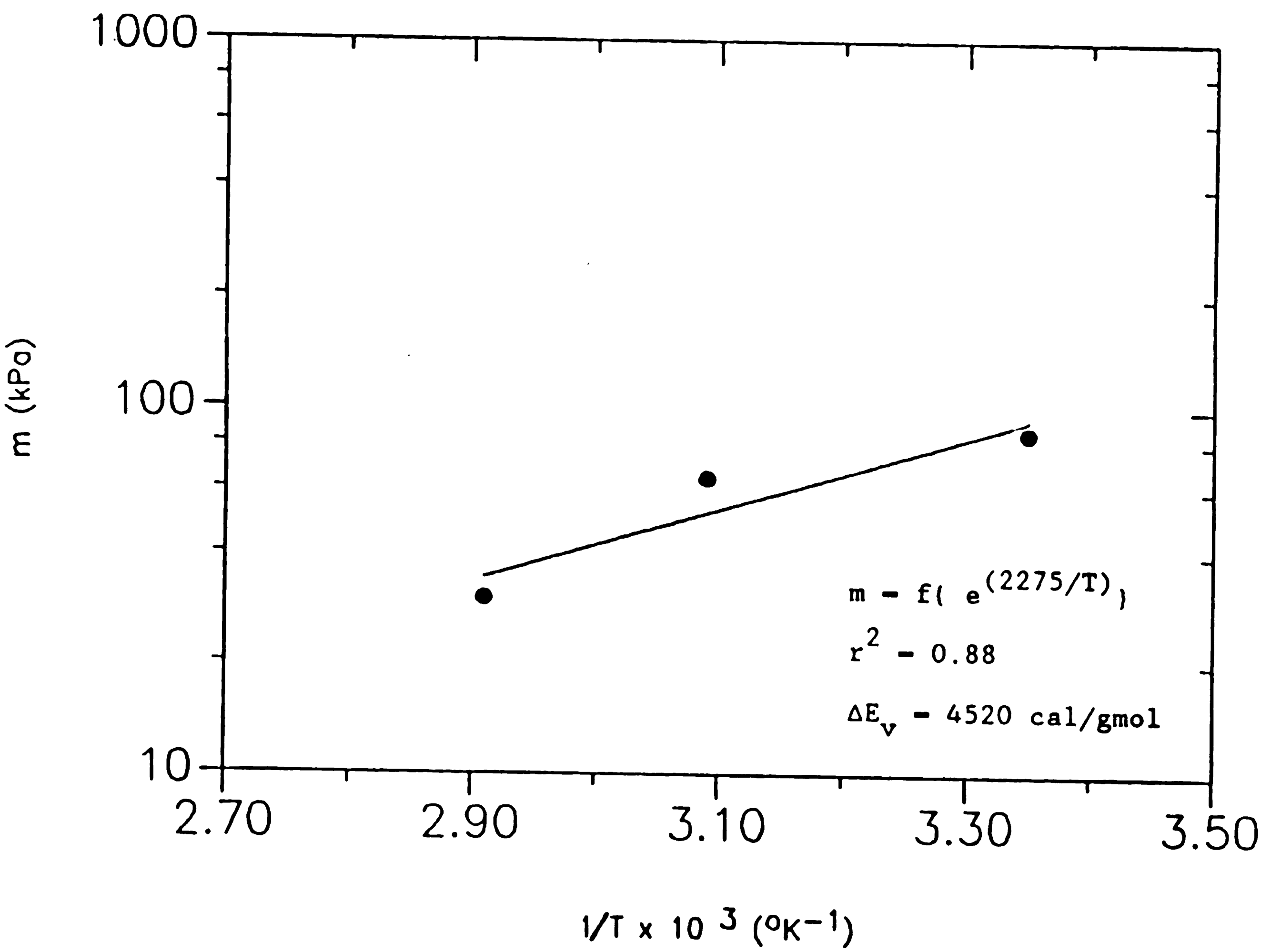


Figure 14. Power law consistency coefficient, m, vs. 1/T for SPS (50% MC) extruded with a capillary rheometer (data points are means of four observations).

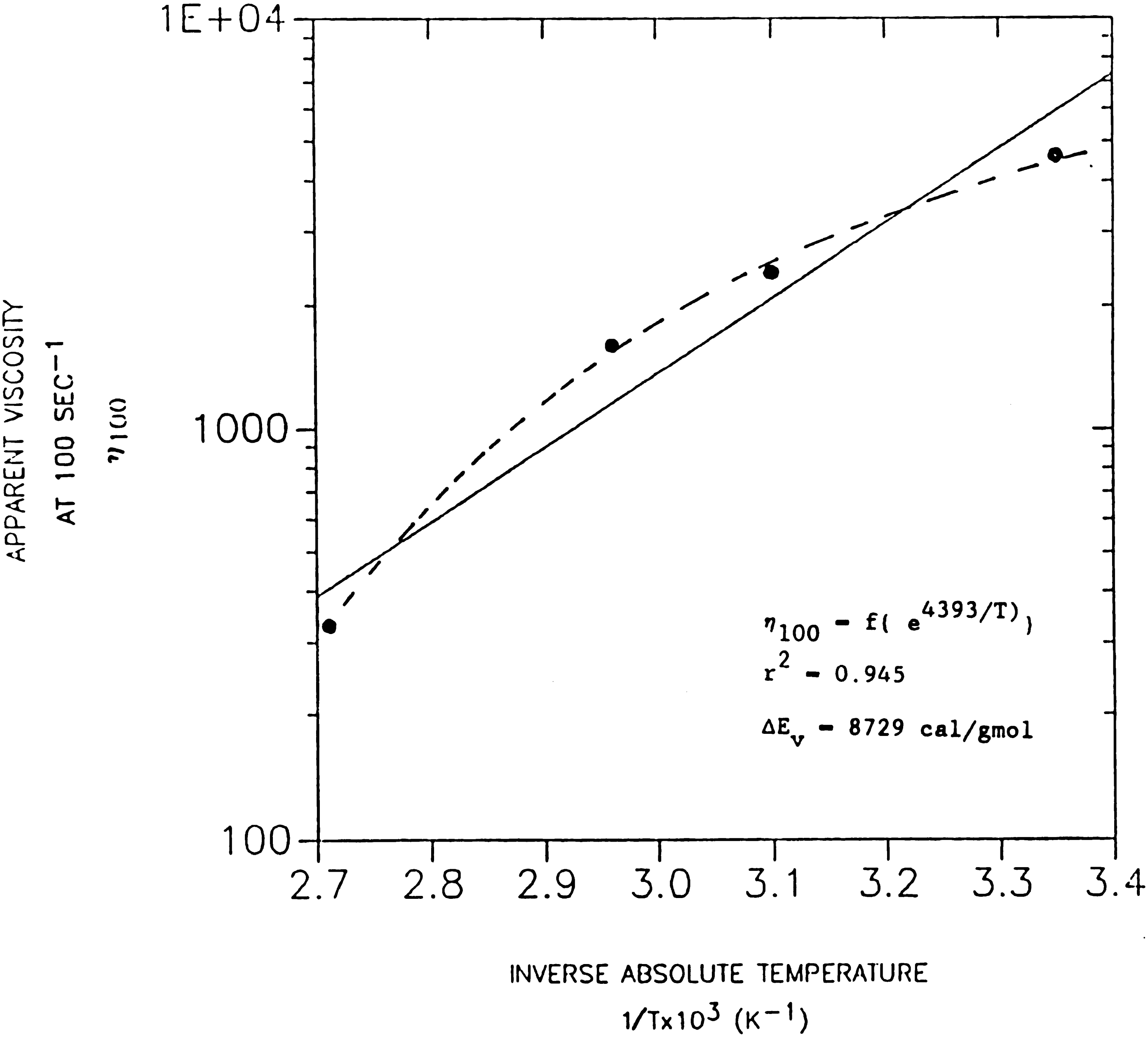


Figure 15. η vs. 1/T for potato dough (33.7% MC) (Apparent viscosity adjusted to γ = 100 sec^{-1}) (Mackey et al. 1986).

TWIN-SCREW EXTRUDER OPERATION

Moisture content/product rate calibration values for SPS and defatted soy flour (Table 11) indicate that the calibrated moisture contents for each product rate were the same, although they were below the predicted moisture content. Moisture contents of extruded potato flour were not obtained as the moisture samples case hardened upon oven drying, causing the release of moisture from the samples to be impossible. From the moisture content prediction results of the defatted soy and SPS calibrations (Table 11), it was assumed that correction of pressure for moisture content of all three materials was unnecessary. The moisture content of potato extrudate was assumed to be 50 percent as Table 11 indicates that the moisture content calibrations of both SPS and defatted soy dough predicted within four percent of their measured moisture contents. The measured product rates did not fluctuate significantly during the extrusion runs and hence, measured product rates were used in the calculation of shear rate. By comparing the moisture content fluctuation of SPS and soy dough (Table 11) it is concluded that use of the parastolic pumps gave a much more stable water injection rate.

Use of a strip chart recorder as opposed to a digital pressure readout for recording pressure is highly recommended for pressure measurement as the extruder operator can easily see when the die pressure is stable. Also, use of a pressure transducer with a maximum range just above the maximum pressures measured would increase the accuracy of the pressure readings.

Table 11. Moisture content and product rate calibration values for SPS and defatted soy flour.

SPS CALIBRATION

MC_{pred} (%)	$\overline{MC}^{(1)}$ (%)	$C.V._{MC}^{(1)}$ (%)	$\overline{MC}^{(2)}$ (%)	$C.V._{MC}^{(2)}$ (%)	$\dot{M}_{pred}^{(3)}$ (kg/s)	$\dot{M}_{meas}^{(3)}$ (kg/s)	$C.V._{\dot{M}}$ (%)
58.6	57.3	1.1	58.0	1.7	0.0088	0.009	2.9
58.6	57.9	1.4	58.0	1.7	0.0138	0.0142	1.9
58.6	58.9	1.5	58.0	1.7	0.0189	0.0195	2.9
64.8	63.8	1.6	64.3	1.5	0.0088	0.0089	5.0
64.8	64.3	1.4	64.3	1.5	0.0138	0.014	1.7
64.8	64.8	1.4	64.3	1.5	0.0189	0.0195	1.2

DEFATTED SOY DOUGH CALIBRATION

MC_{pred} (%)	$\overline{MC}^{(1)}$ (%)	$C.V._{MC}^{(1)}$ (%)	$\overline{MC}^{(2)}$ (%)	$C.V._{MC}^{(2)}$ (%)	$\dot{M}_{pred}^{(3)}$ (KG/s)	$\dot{M}_{meas}^{(3)}$ (KG/s)	$C.V._{\dot{M}}$ (%)
44	41.6	2.3	40.0	4.8	0.0088	0.0103	7.1
44	38.9	2.4	40.0	4.8	0.0113	0.0124	4.2
44	40.2	4.6	40.0	4.8	0.0138	0.0152	2.7
44	38.3	2.5	40.0	4.8	0.0151	0.0171	1.7
44	41.0	4.6	40.0	4.8	0.0176	0.0191	2.5

(1) Average MC (wet basis) for each predicted MC and product rate, $\dot{M}$.
(2) Average MC (wet basis) for each predicted MC (all product rates).
(3) Product rate measured as mass per 30 sec.
(C.V. is coefficient of variance based on 60 to 80 data points)

RHEOLOGICAL PROPERTIES OF TSE DATA

Appendices J to L give the raw data for extruded SPS, potato flour, and defatted soy flour respectively. Barrel temperatures were below the denaturation threshhold temperature (70°C) for defatted soy flour, hence pressure need not be corrected for temperature-time history. In order to reduce viscosity change due to shear history, all potato dough data with work inputs above 0.0002 kw-hr/kg were assumed to be altered by high viscous dissipation and shear effects and were thus excluded from the analysis. This accounted for about five percent of the potato data. Work input did not vary significantly during soy dough or SPS extrusion.

Shear stress vs. shear rate values are given in Appendices M to P and are plotted in Figures 16 to 19 with the corresponding rheological model determined by use of the capillary rheometer. Each τ_w value is the combination of four data points: two duplications of two die lengths. Table 12 gives a summary of Power law coefficients for each extruded material. Viscosity was adjusted to the midrange of the measured extruder die temperatures.

TABLE 12. **Rheological properties of twin-screw extruder data**

MATL	MC_{Ref} (%)	T_{Ref} (°C)	m (KPa)	n	r^2	m(CR)[1]	n(CR)[1]
SPS	58.0	66.6	132.8	.27	0.80	32	.23
SPS	64.3	59.3	76.7	.28	0.93	--	.23
POTATO	50	54.4	0.501	.85	0.82	11	.25
DSF	40.0	46.8	40.8	.23	0.60	10.3	.5

1. Capillary rheometer values adjusted to twin-screw extruder moisture content and temperature. (Missing m value for 64.3 % MC SPS due to lack of moisture correction factor for SPS)

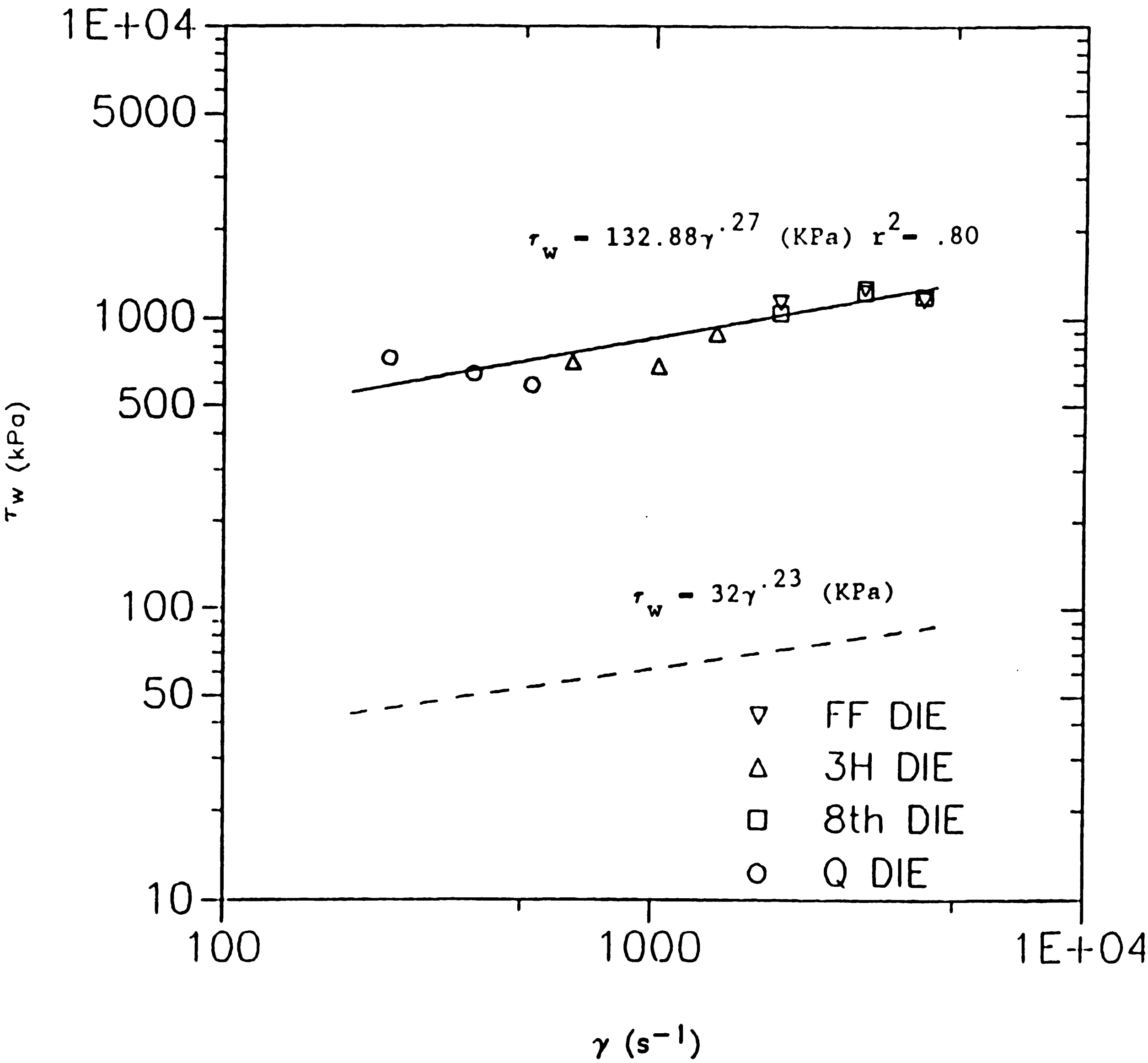


Figure 16. Shear stress vs. shear rate for SPS (58% MC, 66.6°C) (data points are means of four observations).
—— indicates twin screw extruder prediction
--- indicates capillary rheometer prediction

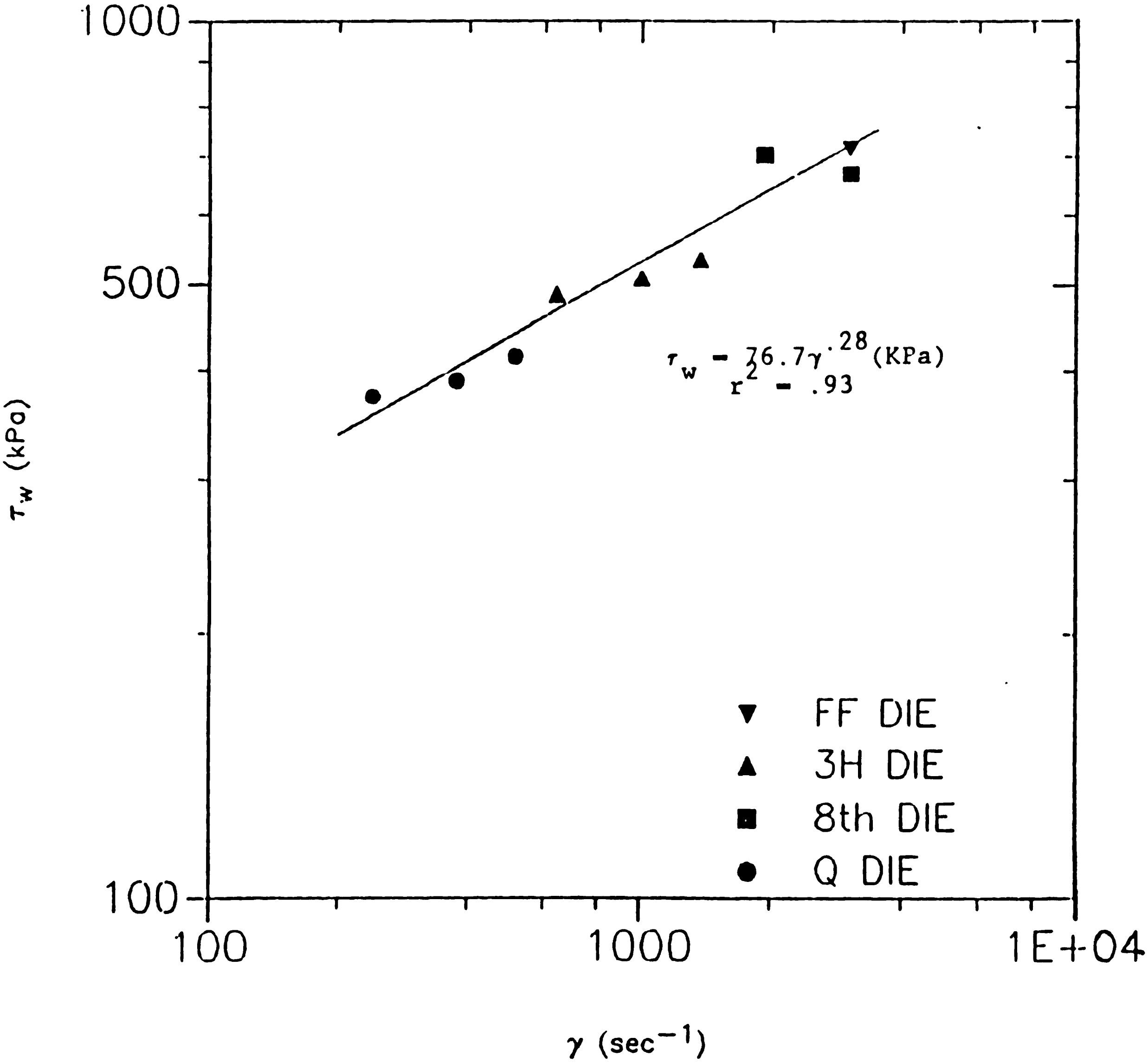


Figure 17. Shear stress vs. shear rate for SPS (64.3% MC, 59.3°C) Twin screw extruder data (data points are means of four observations).

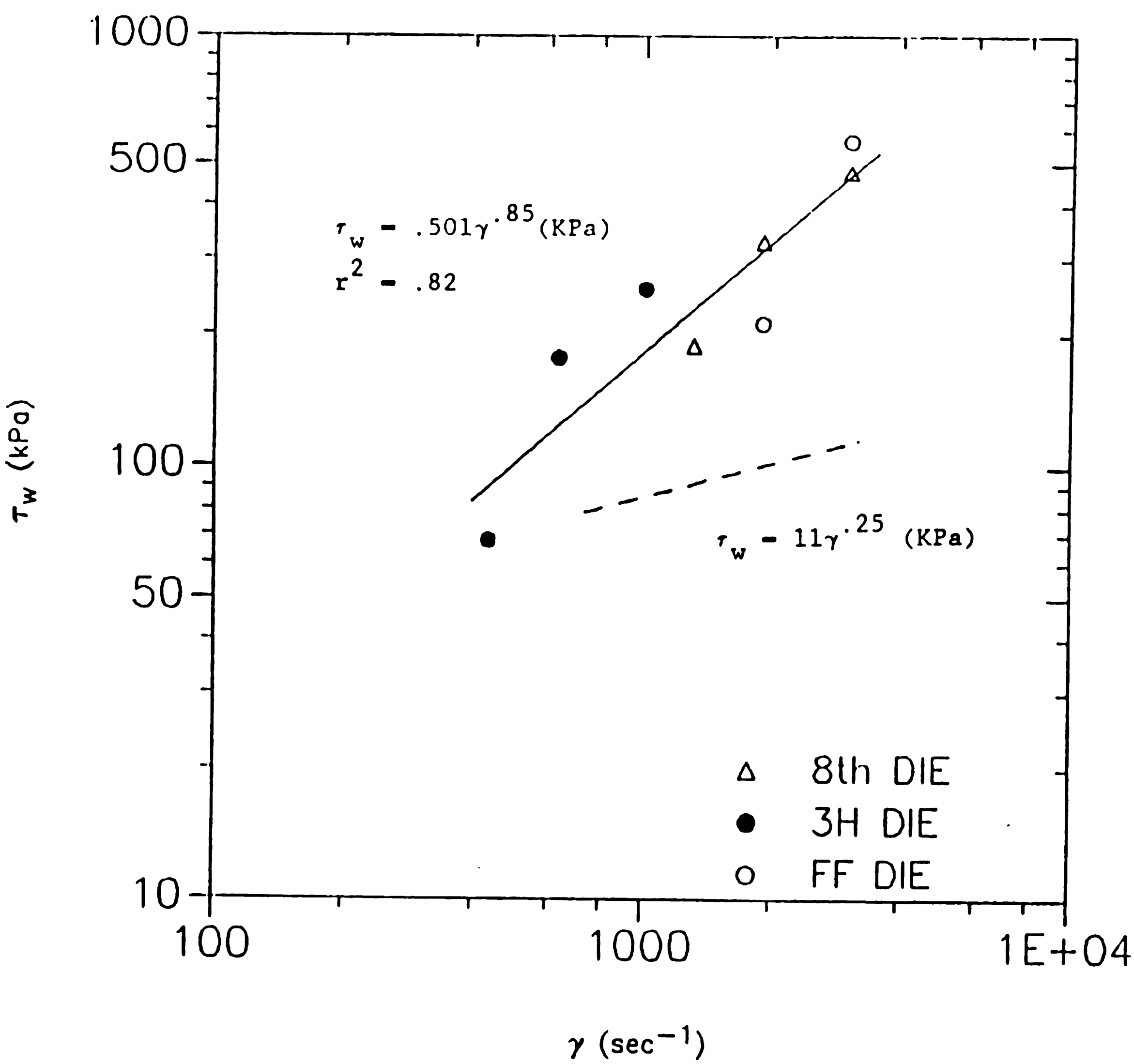


Figure 18. Shear stress vs. shear rate for potato dough (MC=50%, T=54.4°C) (data points are means of two to four observations).
—— indicates twin screw extruder prediction
--- indicates capillary rheometer prediction (Mackey et al., 1987)

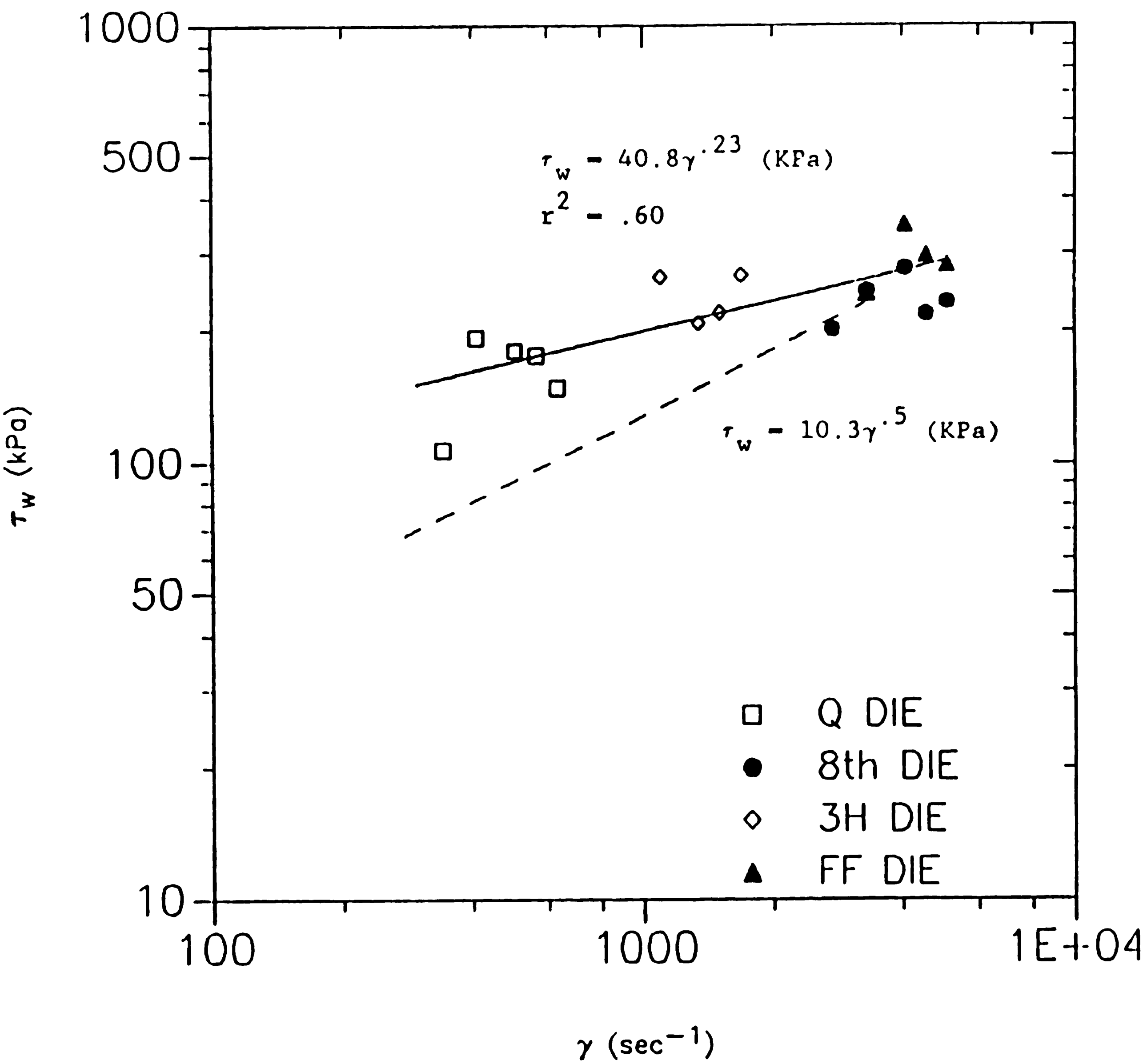


Figure 19. Shear stress vs. shear rate for defatted soy dough (MC=40.0, T=46.8°C) (data points are means of four observations).
—— indicates twin screw extruder prediction
--- indicates capillary rheometer prediction (Morgan et al., 1987)

Note the differences between each of the extruded Power-law parameters and its corresponding capillary rheometer parameters. There are several reasons for these differences. Sample preparation of material for the CR and the TSE were very different. Potato and defatted soy dough tested on the CR was hydrated and allowed to equilibrate whereas the material for the TSE was mixed together and extruded through the dies within a one to two minute residence time. Although the SPS was prepared differently, it was allowed to cool before reheating in the CR and also was held for ten hours at room temperature during the CR testing. Ten hours was the amount of time it took to run the capillary rheometer tests.

Effects of shear and work input within the extruder are unknown and hence were not accounted for. The potato and defatted soy dough has relatively little shear or work input when hydrated for CR testing as compared to the TSE.

Slip had a significant effect on the pressure recorded during the extrusion tests. 'Sharkskinning' caused by material slipping and catching on the die walls was quite visible during extrusion tests, particularly for SPS. Attempts to adjust for slip using the method summarized by Darby (1976) yielded inconclusive results, as shown in Figure 20.

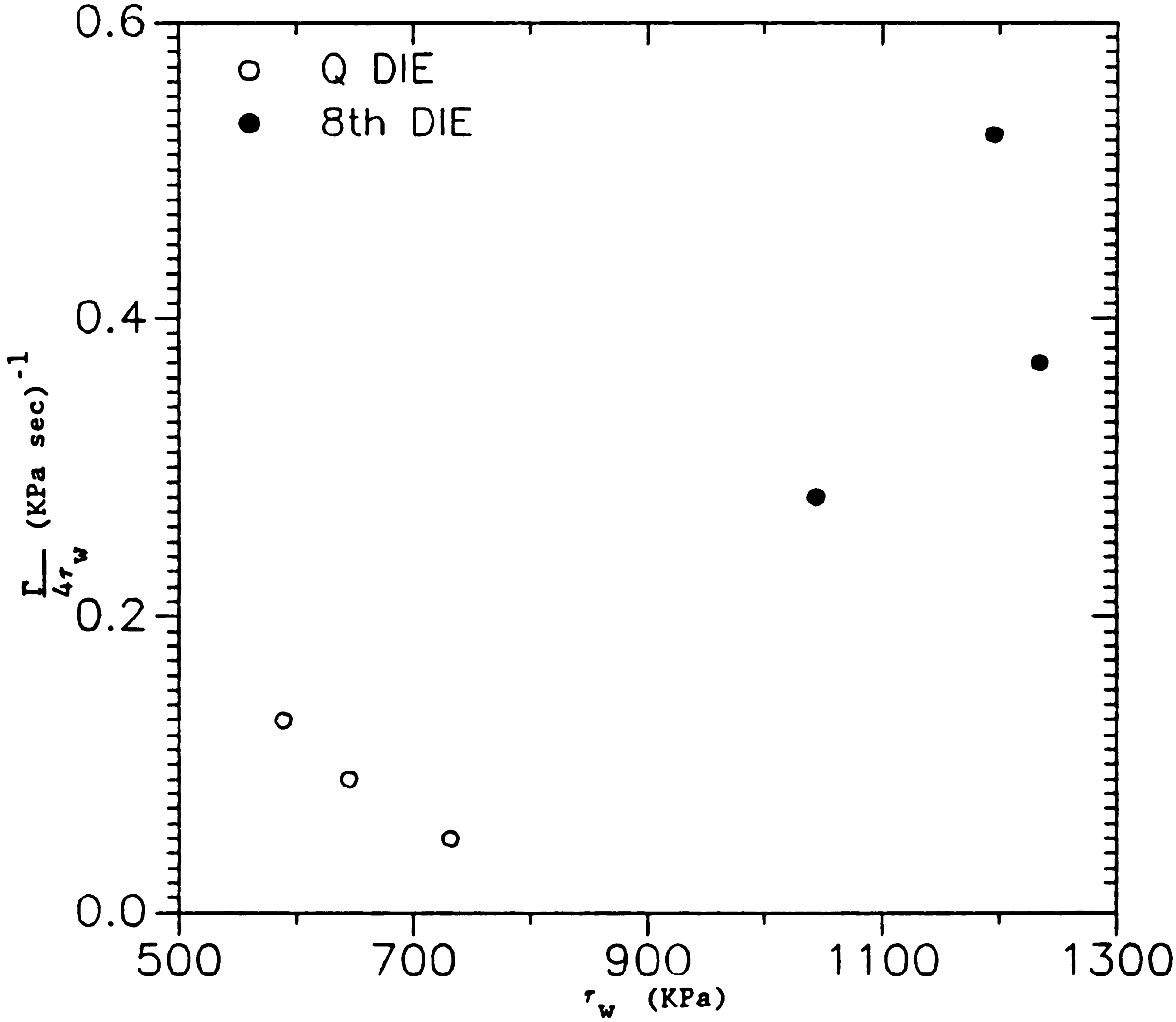


Figure 20. Analysis of slip for SPS TSE data (58% MC) (data points are means of four observations).

The Gentran pressure transducer used to record die pressure has an error of one percent of full scale pressure, resulting in significant error at low pressure readings. Fluctuations in die temperature and moisture content were adjusted for by means of coefficients developed on the capillary rheometer which may not be entirely accurate under extrusion conditions.

Switching between long and short dies induced significant changes in process history, thus the assumption of a constant viscosity material for all die lengths is questionable. This is particularly true for materials susceptable to irreversible physicochemical changes such as defatted soy dough or potato dough. This may partially explain why the τ_w vs. γ data of defatted soy dough and potato dough were scattered much more than the corresponding data of SPS. Furthermore, surging within the extruder at low product rates caused fluctuations in moisture content and product rate. This was very noticeable with use of the Bran & Lubbe injection pump as is seen by comparing the coefficient of variation of moisture content of defatted soy to that of SPS. For the above reasons, it is understandable that the correlation coefficients were lower for the extruder data.

ELASTICITY

No die swell was observed for SPS and the SPS extrudate appeared to be non-elastic. Die swell (β) values for defatted soy flour ranged from 1.1 to 1.3 but no correlation of the β vs. residence time could be made. The author noticed that the defatted soy dough extrudate exhibited elastic properties. Small balls of the dough could be bounced, and when these balls were stretched, they partially relapsed back to their original shape. However, because die swell was minimal, the elastic

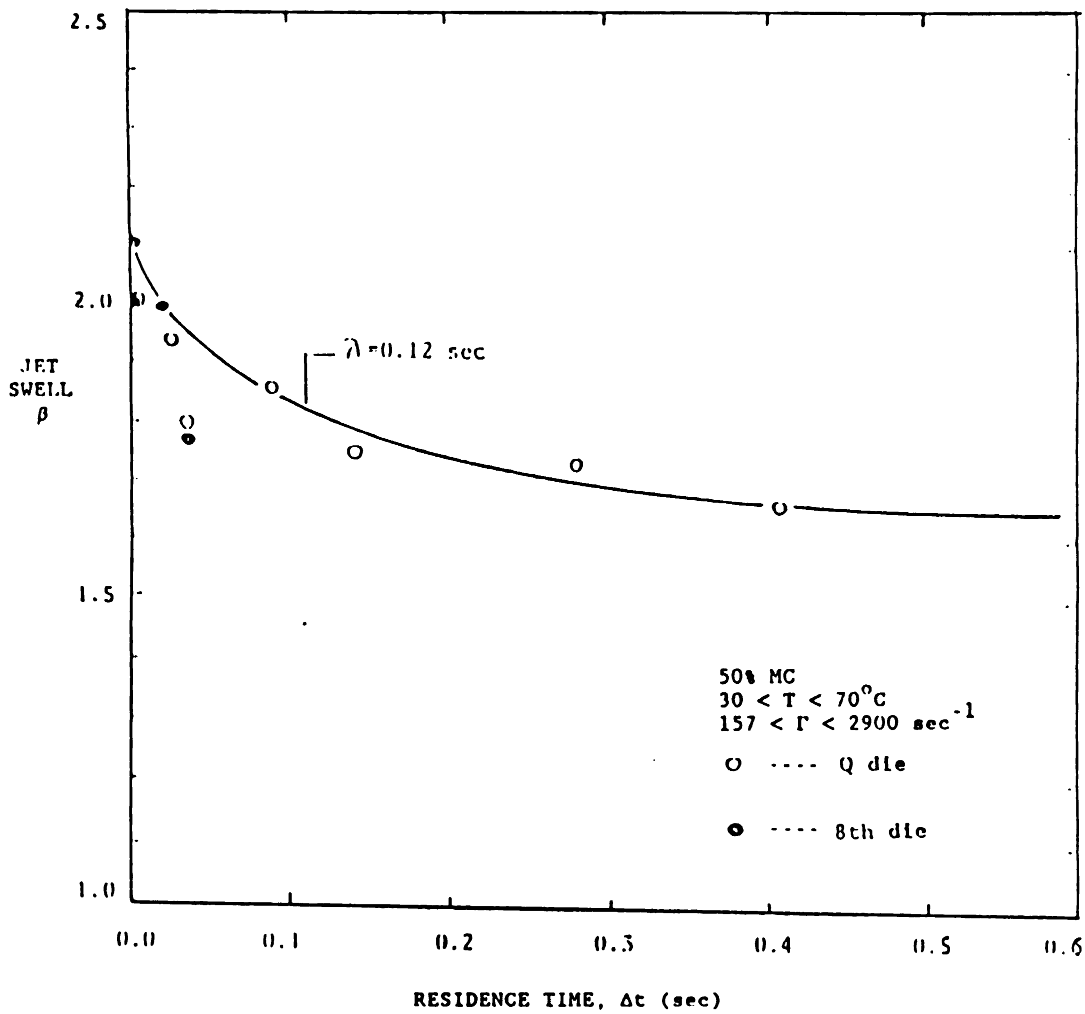


Figure 21. Material time constant determined for extruded potato flour at 50% M.C. (data points are means of two observations).

time constant, λ, was assumed negligible. Figure 21 shows die swell, β, as a function of residence time for potato flour. There is an obvious correlation between die swell and die residence time, however, significant scatter of data at low die residence times made prediction of the time constant difficult. The curve in Fig. 21 was analyzed to obtain λ of 0.12 seconds, measured as the first order time decay constant.

ENTRANCE PRESSURE DROP MODELING

PI (Π) TERM COEFFICIENTS

As the experimental twin-screw extruder results were collected using a twin hole die head, the entrance to the dies was complex and could yield different results than those collected on a single hole die head. For this reason, the flow rate and number of die holes were both divided by two, resulting in the same data that would be given if a single hole die head.

Dies that did not have a full flange 90 degree entrance (Appendix B) were assumed to have an entrance of 180 degrees in this analysis as the angle from the die edqes to the entry cone vertex is approximately 180 degrees.

Observed ΔP_{ent} data and their corresponding Π term variables (Table 2) are given in Appendices Q and R for experimental and published data respectively. Stepwise forward regression (SAS, version 5) was used to obtain the best-fit coefficients of the model form presented in Eqn. (21) by means of the following model transformation:

$$\ln\pi_1 = \ln a+b_2\ln\pi_2+b_3\ln\pi_3+b_4\ln\pi_4+b_5\ln\pi_5+b_6\ln\pi_6+b_7\ln\pi_7+b_8\ln\pi_8 \quad (27)$$

where a equals the exponential of the intercept value given by stepwise regression.

Note that effects of die hole spacing on ΔP_{ent} were not assessed in either experimental or published data and therefore, π_9 is set to one for this study. π_3 and π_4 were not assessed in the published literature, hence coefficients for π_3 and π_4 of the published literature were not developed.

Data were grouped in several different ways to assess effects of model coefficients. The SAS program for computing the Π terms and evaluating their coefficients by stepwise forward regression for each grouping is given in Appendix S. The resulting model correlation coefficient (r^2) and π term coefficients are given in Table 13 for each of the group tested. The complete ANOVA given by SAS for stepwise forward regression is given in appendix T.

The stepwise regression ANOVAs indicate that π_2 had the most significant contribution to the model accuracy, while the rest of the π terms together increased the model accuracy by 1 to 24 percent (Table 14). Because π_3 and π_4 were equal to one for most of the data analyzed, their real contribution to the model may be larger than the ANOVAs indicate. π_3 and π_4 values other than one amount to less than five percent of the entire data set analyzed.

Table 13. Coefficients for Eqn. (21) and their corresponding model r^2 (determined by stepwise forward regression).

GROUP(1)	r^2	a	b_2	b_3	b_4	b_5	b_6	b_7	b_8
1.	.90	0.324	-1.24	-0.915	1.05	2.60	-0.176	-0.143	0.558
2.	.93	0.073	-0.968	--	--	7.74	-1.0	-0.20	-0.907
3.	.82	5.10	-0.763	--	--	4.30	-0.491	-0.322	-0.228
4.	.99	19302	-1.01	--	--	-2.71	-0.235	-1.236	--
5.	.95	89322	-1.18	-0.763	0.85	-5.18	--	-1.63	-0.449
6.	.93	13630	-1.12	-0.244		3.024	0.461	-1.85	0.798
7.	.88	77.8	-.69	--	0.15	0.461	--	--	0.429

(1) SAS groups

1. All literature and experimental data (biological and polymer).
2. All literature data (biological and polymer).
3. Polymer data from the literature.
4. Biological data from literature.
5. Experimental data and biological data from literature.
6. Experimental data.
7. Twin screw extruder data.

-- indicates coefficients that did not reach the 50% confidence level (most of the missing coefficients are due to lack of variation in the data)

Table 14. Contribution of Π terms to model accuracy (determined by partial r^2 given by each term)

GROUP(1)	1. partial	2. partial r^2	3. partial r^2	4. partial r^2	5. partial r^2	6. partial r^2	7. partial r^2
$\ln\pi_2$	0.859	0.839	0.578	0.985	0.919	0.845	0.668
$\ln\pi_3$	0.003	--	--	--	0.001	0.001	--
$\ln\pi_4$	0.002	--	--	--	0.002	--	0.002
$\ln\pi_5$	0.005	0.049	0.183	0.006	0.011	0.003	--
$\ln\pi_6$	0.001	0.024	0.023	0.001	--	-.008	0.02
$\ln\pi_7$	--	0.002	--	0.001	0.012	0.04	--
$\ln\pi_8$	0.014	0.013	0.002	--	0.006	0.026	0.187

(1) SAS groups

1. All literature and experimental data (biological and polymer).
2. All literature data (biological and polymer).
3. Polymer data from the literature.
4. Biological data from literature.
5. Experimental data and biological data from literature.
6. Experimental data.
7. Twin screw extruder data.

-- indicates coefficients that did not reach the 50% confidence level (most of the missing coefficients are due to lack of variation in the data)

VALIDITY OF Π TERM COEFFICIENTS

The π_2 exponent for each group (Table 13) varied from -0.69 to -1.24. The sign of the exponent is intuitively correct because if all variables except Q remain constant, ΔP_{ent} increases as flow rate increases. Also, if the consistency coefficient, m, is increased while all other variables are held constant, π_2 decreases causing ΔP_{ent} to increase. Thus, ΔP_{ent} increases as viscosity increases. This is the same trend that the Boger (1982) model indicates for the relationship between the Reynold's number and ΔP_{ent}.

The exponent of the π_3 term ranged from -0.24 to -0.915 and the sign is intuitively correct. As n_d increases, the fluid becomes less restricted and hence, total pressure drop, including ΔP_{ent}, should decrease. Intuitively a realistic value for this exponent is negative one because pressure drop appears to be linearly related to the number of holes.

It is difficult to intuitively relate effects of π_4 (shape factor) to entrance pressure drop. The coefficient can possibly be related to the relationship between the shape factor and ΔP_{dhole}. As the shape factor increases, the flow coefficient, f_c, (Figure 3) increases. As f_c increases, ΔP_{dhole} decreases (Eqn. 13). If the shape factor has the same relationship on ΔP_{ent} as it does for ΔP_{dhole}, the π_4 coefficient should be a negative value. The exponent for π_4 in groups 1 and 5 of Table 13 are likely to be a statistical anomaly because about 95 percent of the shape factor values are F=1, hence causing uneven weighting of F. The π_4 exponent of group 7 (Table 13) makes more sense statistically as shape factors other than F=1 account for 30 percent of the data of this group. Although the positive sign on this exponent does not intuitively make sense, the small magnitude of this value may indicate that the exponent should be approximately zero. Further analysis of the effect of irregular shaped holes on ΔP_{ent} needs to be made.

Values for the π_5 exponent (Table 13) are erratic in both magnitude and sign. Reduction of the Boger (1982) model by Reynold's analogy indicates that for typical die diameters (0.1 to 0.6 cm) and flow rates ($1x10^{-5}$ to $1x10^{-8}$ m^3/s) used in food extrusion, the Boger (1982) model can be reduced to the following approximation:

$$\Delta P_{ent} = f(0.67\ \gamma^{n}\ n^{-0.89}) \qquad (28)$$

According to Eqn. (28), as n increases (for shear thinning fluids), ΔP_{ent} increases. Since n is inversely related to π_5, ΔP_{ent} decreases as π_5 increases, indicating that the π_5 coefficient would be negative for the Boger (1982) model. Group 4 data of Table 13 (biological data from literature) resulted in an exponent with an intuitively correct (negative) sign. From Appendix Q it is seen that n values, on which π_5 is based, are evenly distributed between 0.22 and 0.63. Data of group 5 (Table 13) also resulted in a negative exponent but this is due to the effect of group 4 data on group 5 as group 5 is made up of groups 4 and 6 and group 6 data resulted in a positive π_5 exponent. Looking at the distribution of n values (Appendices Q and R) of all data groups (Table 13) it is seen that group 4 data are the only ones in which n values are evenly distributed over a wide range. For example, two thirds of the n values in group 3 are 0.33 and the rest of the n values range from 0.6 to 0.8. Therefore, it is concluded that for statistical analysis of π_5, data group 4 of Table 13 is the only group which has normally distributed n values and the sign of the π_5 exponent from group 4 agrees with intuition.

The π_6 coefficients were consistently negative among the groups. This coefficient should be negative because as the cone entrance increases, less resistance to flow occurs. Results of Morgan et al. (1978) can be rearranged to give a π_6 coefficient of -0.73 for defatted soy dough extruded with a capillary rheometer. This compares favorably with the π_6 exponent of -0.23 to -1.0 in Table 13. The one exception occurs in data group 6 (experimental data from this study) with a positive exponent of 0.46. A possible explanation for this exponent is an anomaly produced by the combining of data collected by two very different techniques: capillary rheometry and twin-screw extrusion.

All π_7 coefficients are consistently negative, but there is considerable variance in its order of magnitude with a range of -0.2 to -1.85. The value of the π_7 coefficient for the experimental data appears to be too large as Han (1973) showed little change in ΔP_{ent} for entrance angles of 90 deg. to 180 deg. for polymers. This is particularly true for highly viscous materials because they tend to build up in the corner of the entrance region, creating their own entrance angle approximately equal to 90 deg. At first glance, the negative exponent for the entrance angle term appears to be contrary to intuition. However, Han (1973) showed that for polymer melts, entrance pressure was inversely correlated to entrance angle for greater than 60 deg. This is explained by the increase in entrance cone length for small α.

The π_8 coefficient also varied significantly among the groupings (Table 13). The computed π_8 term for experimental data added much variance to the π_8 coefficient as the elastic time constant, λ, was calculated by a different technique and resulted in a much larger λ than was observed for polymer data. Although the large time constant may be accurate it was only proposed as an alternative constant. Further research must be conducted to determine how this alternative time constant corresponds to time constants determined by other techniques.

ENTRANCE PRESSURE PREDICTION ACCURACY

Because the Π term coefficients were developed by use of linear regression of parameters transformed to the log space (Eqn. 27), any error in the model is exponentially magnified when converting to the form of Eqn. 21. For example, the model developed for all data shows good correlation for the predicted vs. observed π_1 term (Figure 22). However, the resulting predicted vs. observed correlation for entrance pressure drop is poor (Figure 23). Much of the problem encountered is due to the fact that the model is applied to a vast range of entrance pressure drop data (nine decades) and materials. Hence, further regression analysis was performed to apply the model to individual groups of data bases on material type and source. Linear regression was used to predict the accuracy of Eqn. (29) for the individual groups (Appendix U). As expected, coefficient values developed by linear regression analysis were similar to those developed by stepwise forward regression. Table 15 gives the model coefficients developed for each data group, and its corresponding fit for predicted vs. observed ΔP_{ent}, where predicted ΔP_{ent} is calculated as follows:

$$\Delta P_{ent} = \frac{\rho Q^2}{16 n_d^2 r_h^4} \left[a(\pi_2)^{b_2}(\pi_3)^{b_3}(\pi_4)^{b_4}(\pi_5)^{b_5}(\pi_6)^{b_6}(\pi_7)^{b_7}(\pi_8)^{b_8}\right] \quad (29)$$

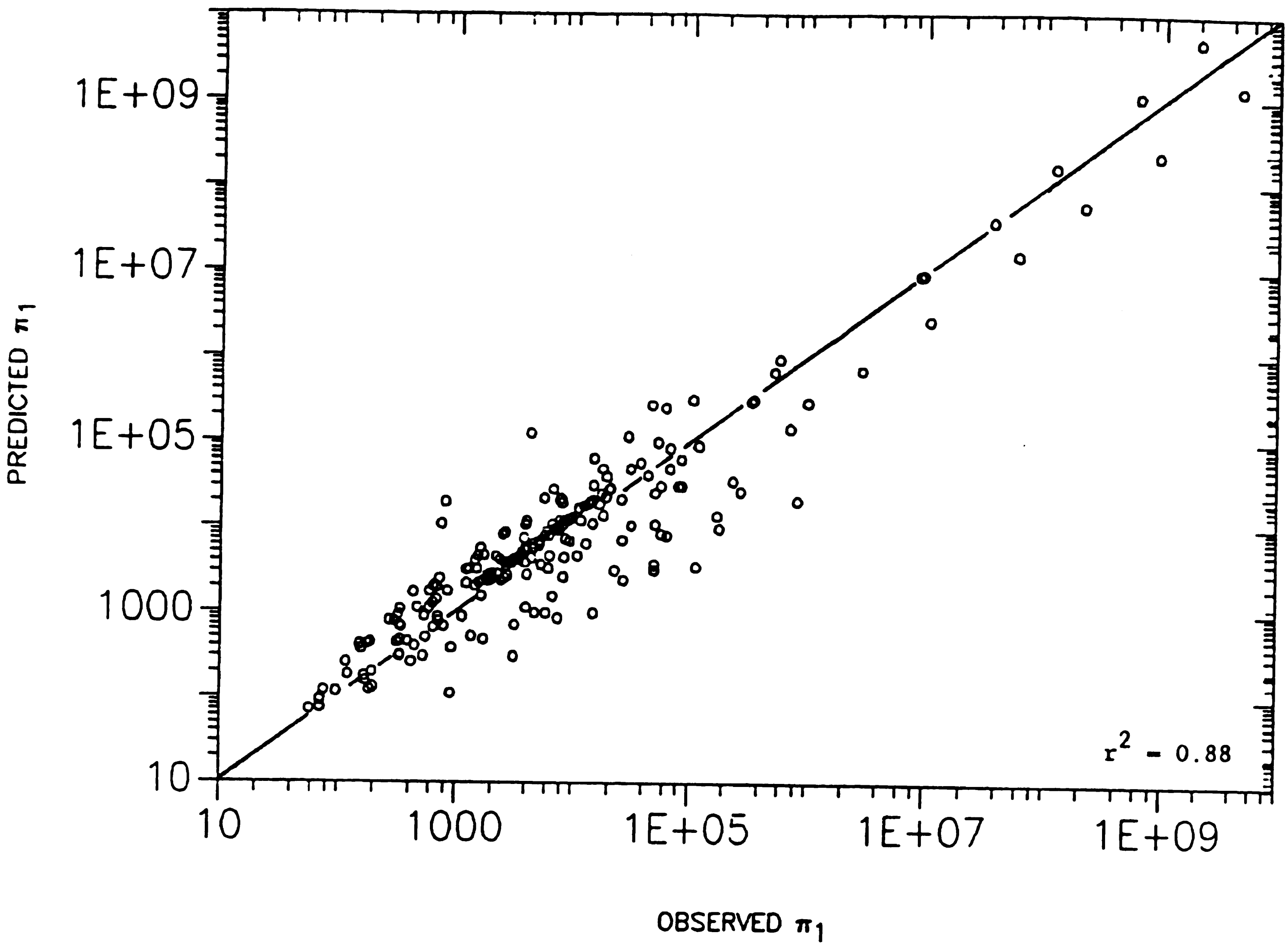


Figure 22. Predicted vs. observed π_1 for all published and experimental data.

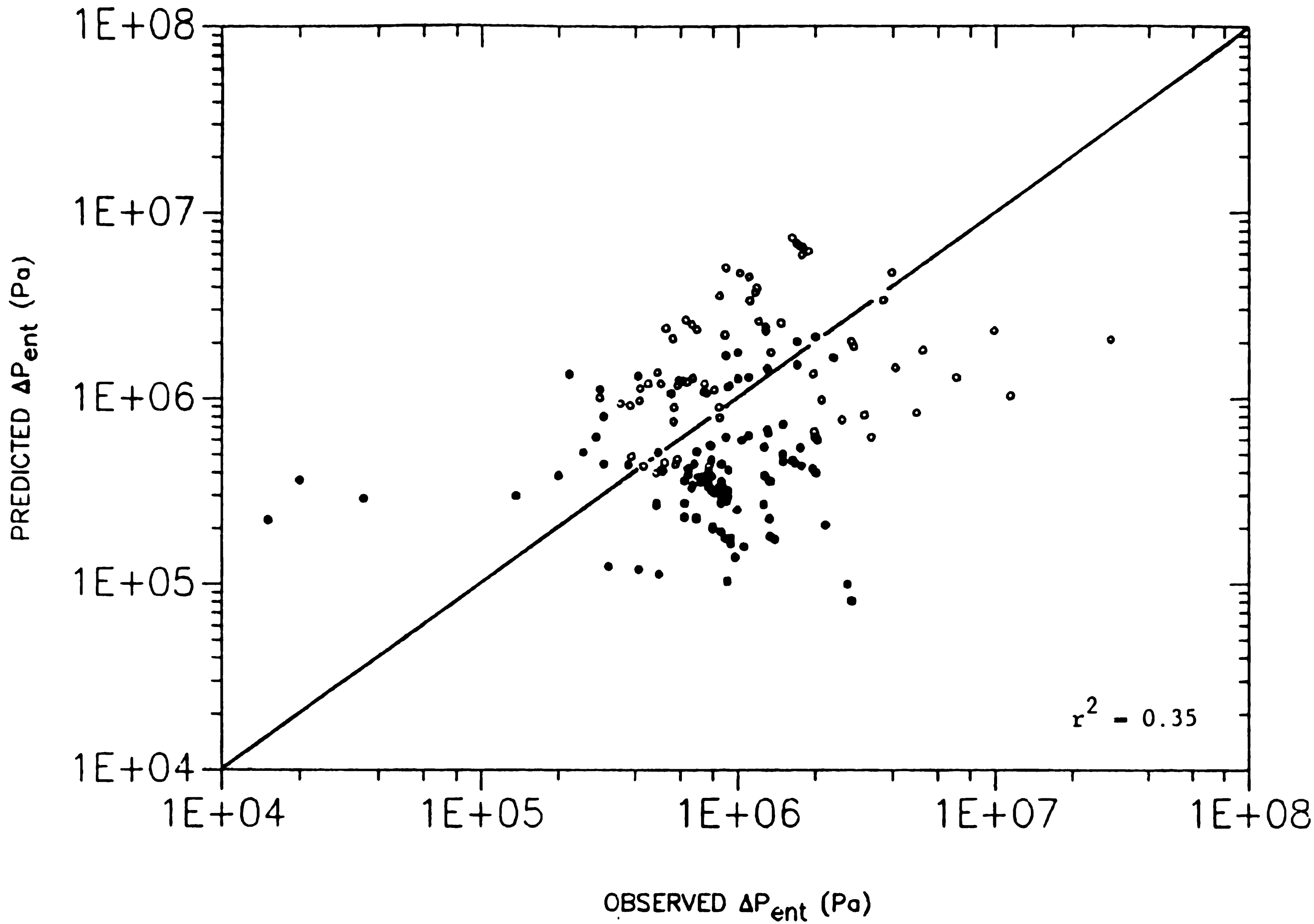


Figure 23. Predicted vs observed ΔP_{ent} for all published and experimental data (solid points are plastic polymers and open points are food doughs).

Table 15. Coefficients for Eqn. (28) and the correlation coefficients (r^2) for ΔP_{ent} predicted by Eqn. (28) vs. observed ΔP_{ent}.

GROUP(1)	r^2	a	b_2	b_3	b_4	b_5	b_6	b_7	b_8
1.	.93	5.10	-0.763	--	--	4.30	-0.491	-0.322	-0.228
2.	.89	19312	-1.01	--	--	-2.71	-0.23	-1.23	--
3.	.90	125.1	-0.667	-0.013	0.191	-0.676	0.488	0.032	0.310
4.	.99	7.46	-1.20	0.010	0.408	--	--	-0.07	-0.05
5.	.86	2.49	-1.01	0.187	0.011	--	-0.11	-0.02	--
6.	.99	0.88	-1.15	-0.483	0.29	-1.18	-0.22	-0.06	--

(1) SAS groups

1. Polymer data from the literature.
2. Defatted soy dough data from literature.
3. Twin screw extruder experimental data.
4. Potato dough collected on twin screw extruder.
5. Defatted soy dough data collected on twin screw extruder.
6. SPS data collected on twin screw extruder.

As seen from the correlation coefficients in Table 15, the model fits well for groups of data of the same material or data collected on the twin screw extruder. Note that the model fits well for published polymer data collected by several different techniques by different researchers (group 1, Table 15). Likewise, the model fit well for published defatted soy dough data collected by different researchers (group 2, Table 15). Figures 24 to 29 show the predicted vs. observed ΔP_{ent} for the following data groups respectively: published polymer, published defatted soy dough, twin screw extruder, extruded potato dough, extruded defatted soy dough, and extruded SPS. The model given by Boger (1982) had a much lower accuracy as shown in Figure 30.

Because some of the Π terms coefficients had a wide variation, it is recommended that the coefficients be redeveloped for specific applications. Results from stepwise forward regression (Table 14) indicate that several Π terms did not contribute significantly to the model accuracy. A five percent increase in the model r^2 was chosen as a criterion for minimum contribution to the model r^2. With this standard, the final model form for predicting ΔP_{ent} is as follows:

$$\Delta P_{ent} = \frac{\rho Q^2}{16 n_d^2 r_h^4} [a(\pi_2)^{b_2} (\pi_5)^{b_5} (\pi_8)^{b_8}] \qquad (30)$$

Research conducted in fluid mechanics (Kim-E et al.,1983) indicates that entrance pressure is highly dependent upon the contraction ratio. The author hypothesizes that the contraction ratio was not found to be significant in this study because of the small Reynold's numbers found in food extrusion (Re<<1). Because the Reynold's number is small, inertial forces are small relative to viscous forces and hence, pressure drop due to change in flow direction in the die entrance is insignificant compared to pressure drop due to change in the material viscous and elastic properties. If the model is to be applied in cases with a high Reynold's number, the following model form is recommended:

$$\Delta P_{ent} = \frac{\rho Q^2}{16 n_d^2 r_h^4} [a(\pi_2)^{b_2} (\pi_5)^{b_5} (\pi_6)^{b_6} (\pi_8)^{b_8}] \qquad (31)$$

Because of the large change in die hole pressure drop correction for shape factors less than 0.5 (Figure 3), it is probable that small shape factors will also effect ΔP_{ent} significantly. Further research needs to be done on the effect of small shape factors (e.g. slits or sharp edged cross sections) on the accuracy of the ΔP_{ent} model. As π_3, the number of die holes, had negligible effect on the accuracy of the model, it is assumed that the π_9 term also would not contribute to the model accuracy. Note that for non-elastic fluids the π_8 term can be eliminated and for Newtonian fluids the π_5 term can be eliminated. As

Eqn. (30) requires no specific die geometry, the remaining π coefficients and rheological properties can be gathered simultaneously by use of a die with multiple pressure taps. Han (1973) shows the application of a multiple pressure tap die for collecting ΔP_{ent}, ΔP_{ex}, and rheological properties of plastic polymers and van Zuilichem et al. (1983) gives the design of a slit die for measuring the rheological properties of protein and starch doughs. The author cautions against using a slit die with a small aspect ratio (H/W) until further research is done on the effects of entrance to narrow slits and die cross sections with sharp corners. Use of a slit die would eliminate changing long and short dies but may still require temperature correction due to cooling of the material along the die length. Therefore, temperature should be measured at points along the die.

As the combined twin screw extruder data and each separate extruded material data all resulted in a good model fit, it is concluded that the model is effective for extrusion applications such as scale-up, die modification, and change of material. For scale-up or die modification where the material rheological properties remanin constant, π_5 does not change and hence can be excluded from the model as it becomes part of the constant, a. A step by step procedure is outlined in Appendix V for experimental testing and data analysis procedures for total pressure drop modelling in food extrusion applications.

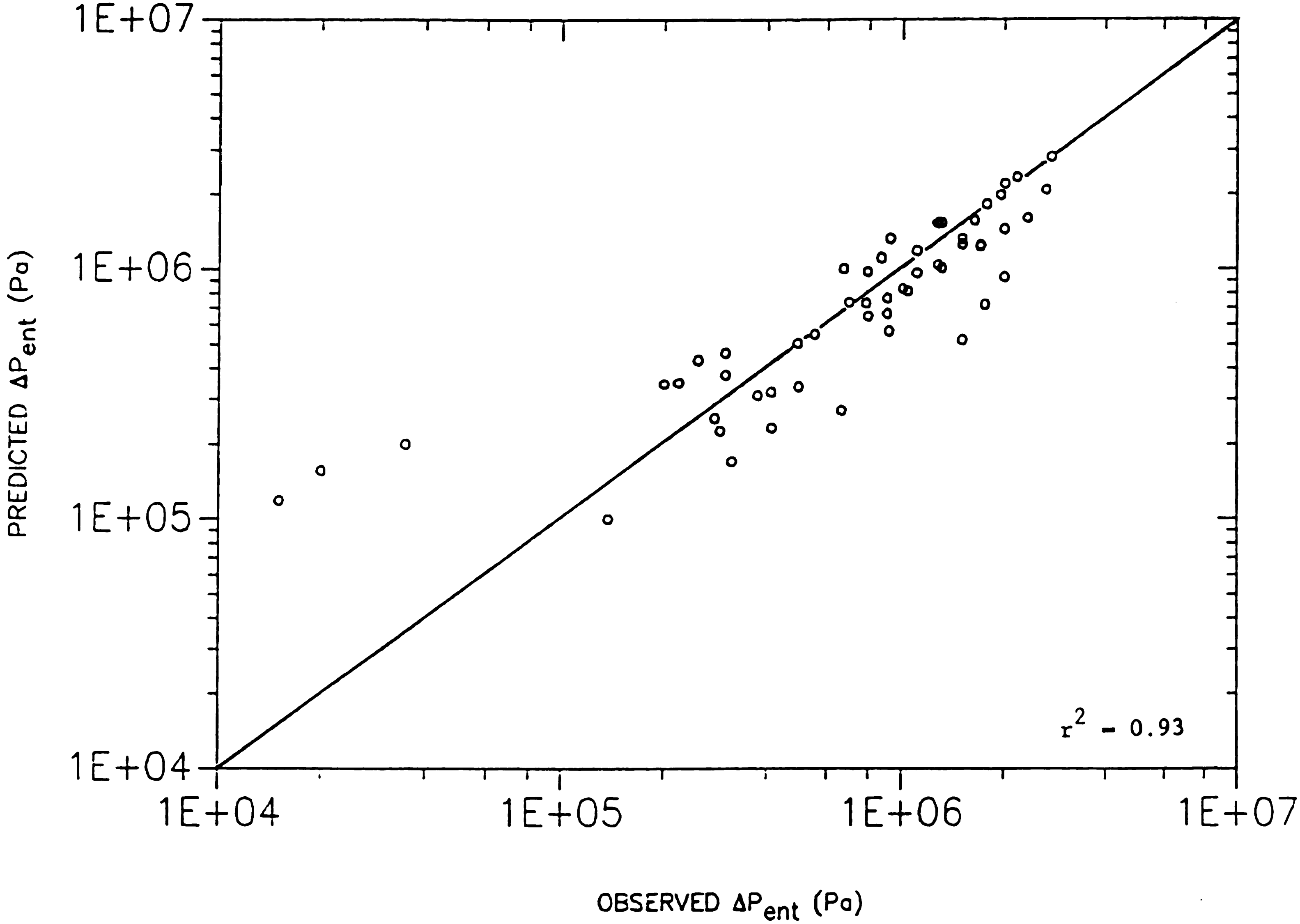


Figure 24. Predicted vs. observed ΔP_{ent} for published polymer data.

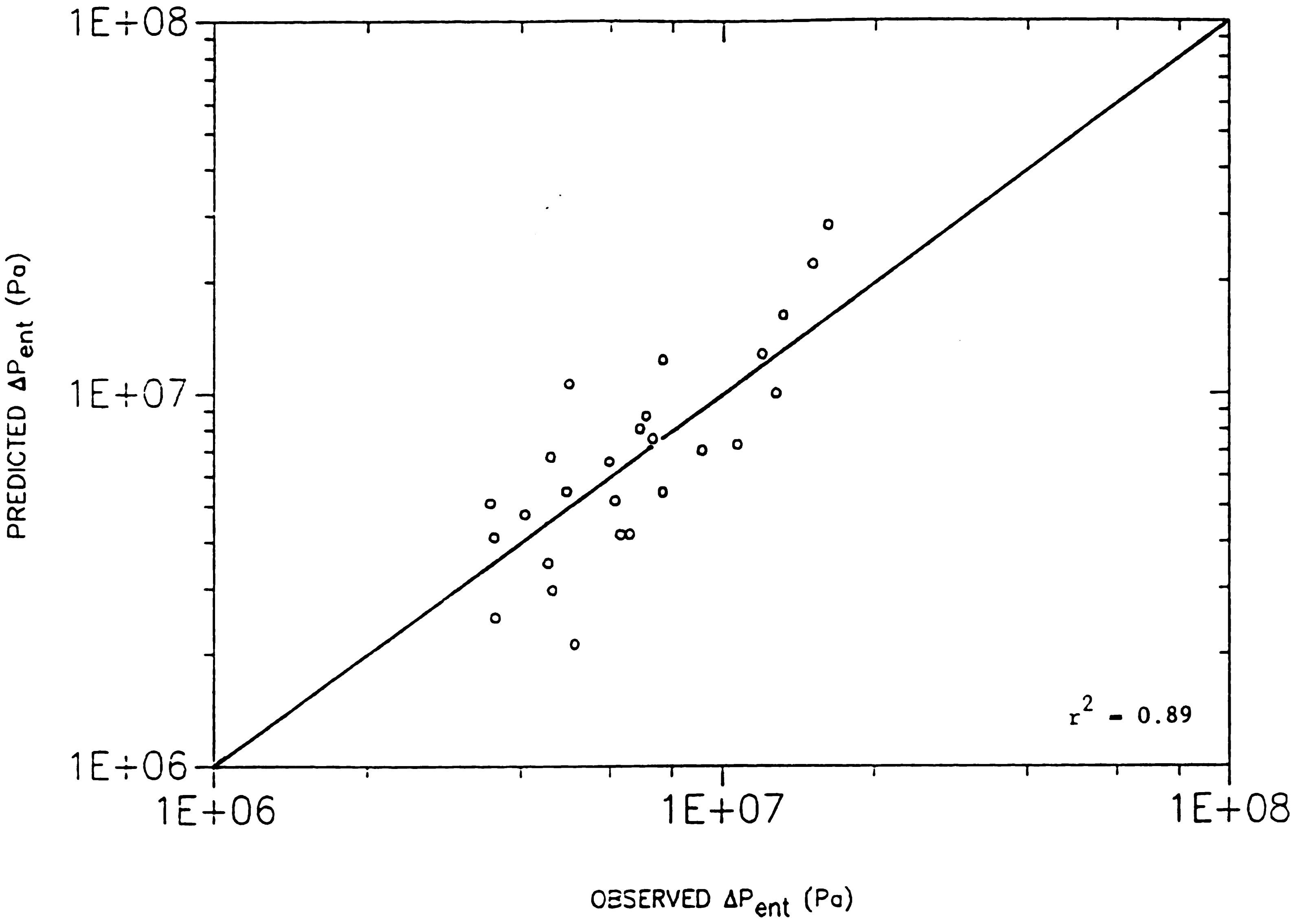


Figure 25. Predicted vs observed ΔP_{ent} for published defatted soy data.

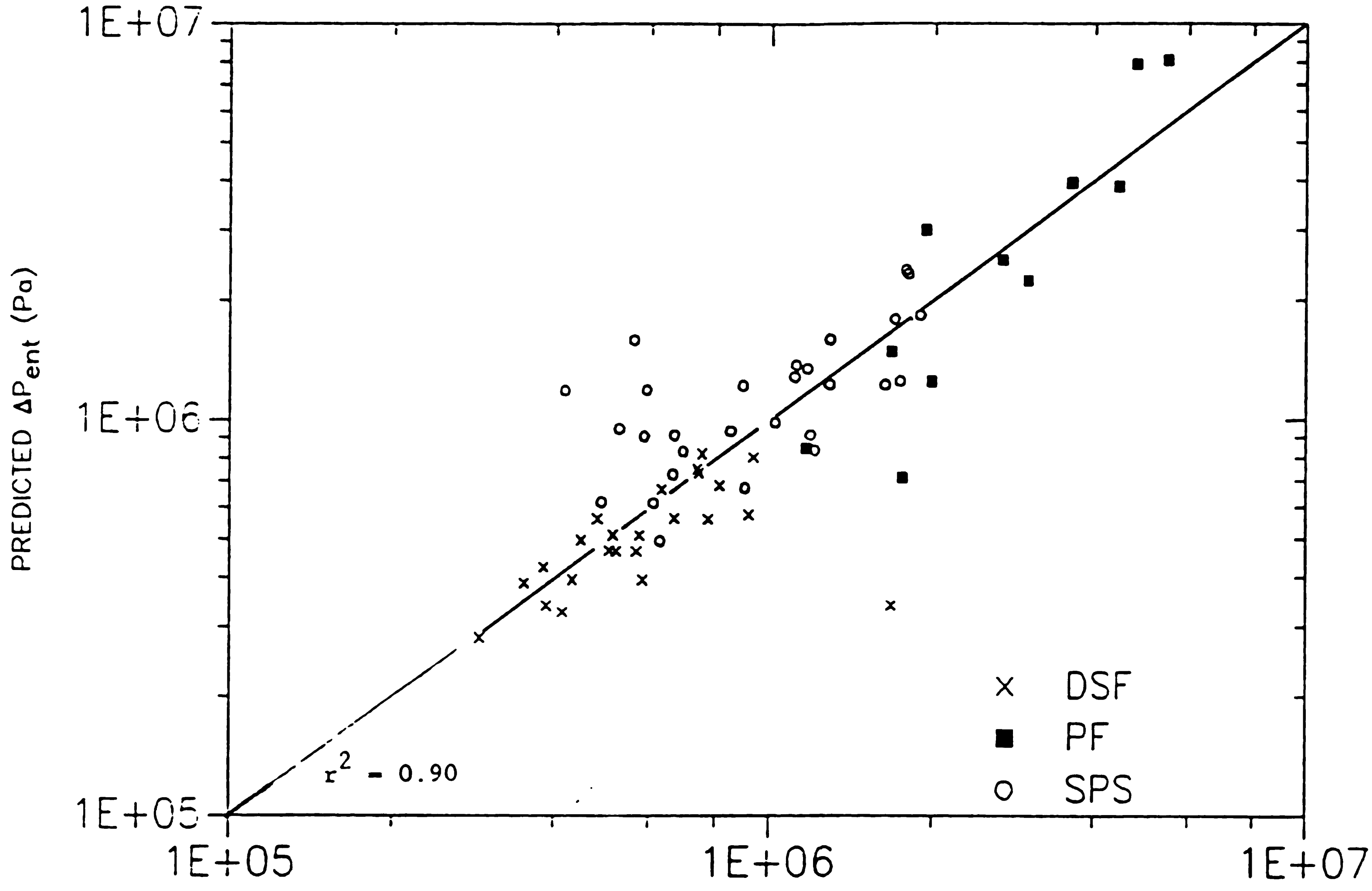


Figure 26. Predicted vs. observed ΔP_{ent} for twin screw extruder data (data points are means of four observations).

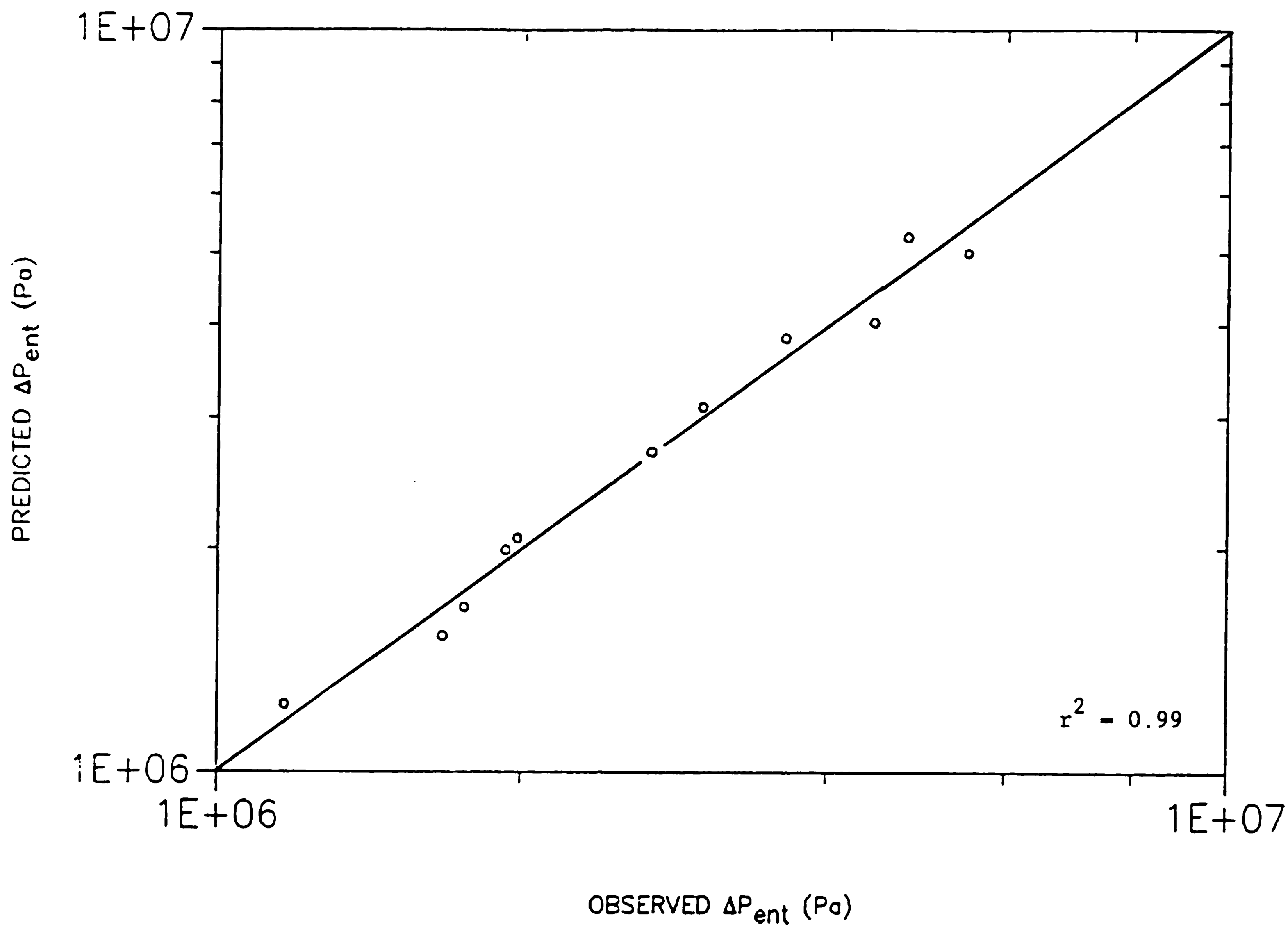


Figure 27. Predicted vs. observed ΔP_{ent} for extruded potato dough data (data points are means of two to four observations).

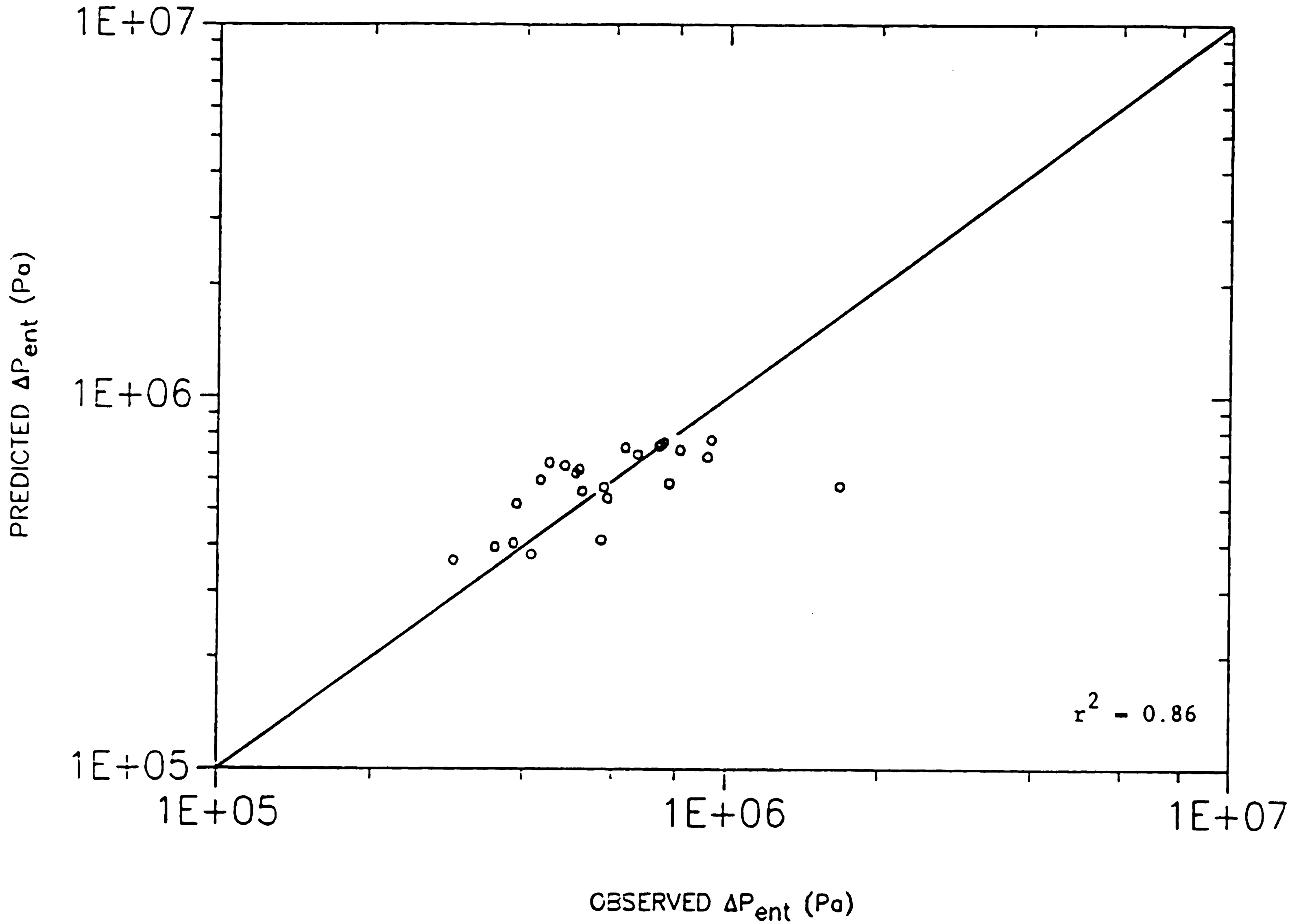


Figure 28. Predicted vs. observed ΔP_{ent} for extruded defatted soy dough data (data points are means of four observations).

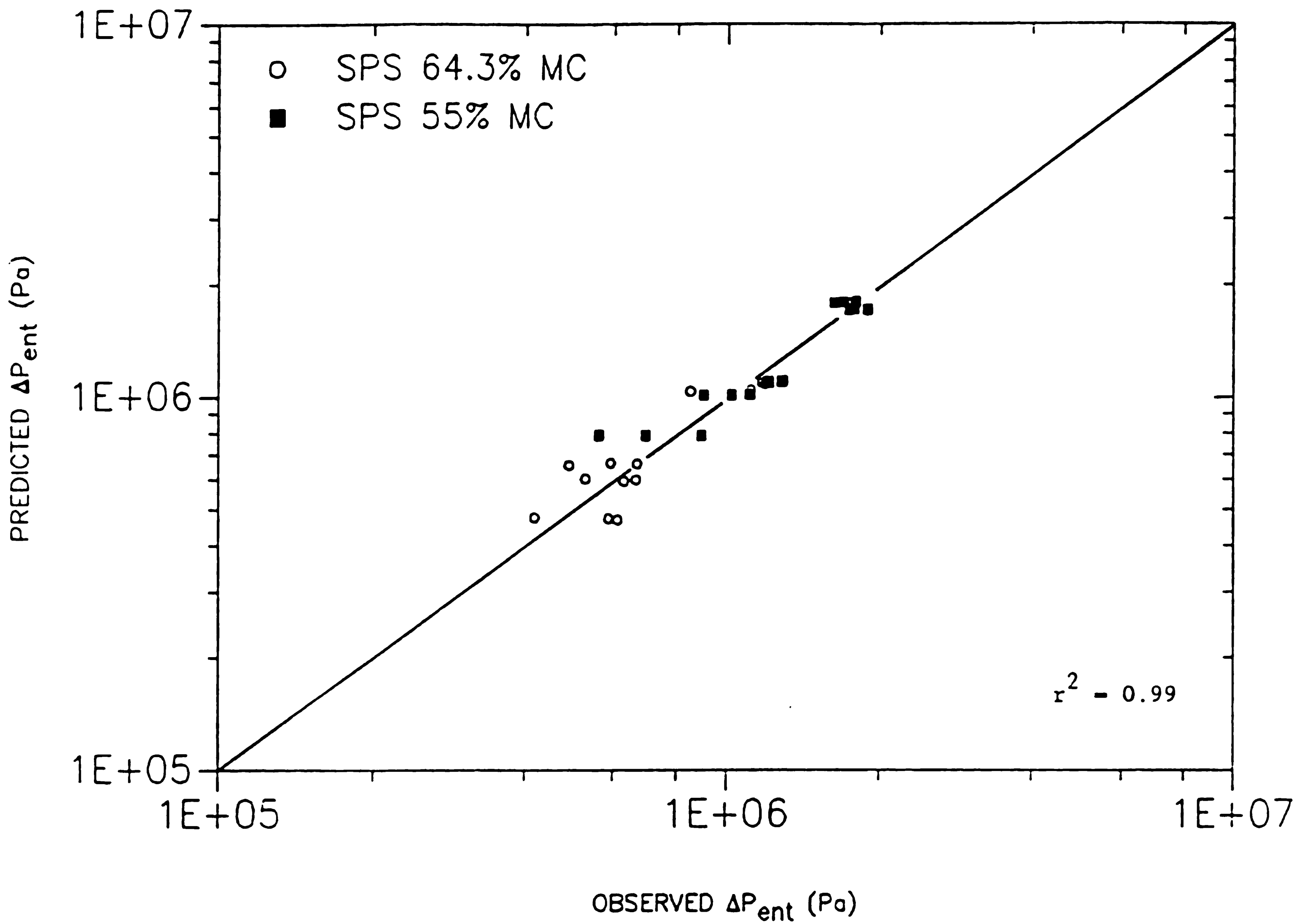


Figure 29. Predicted vs observed ΔP_{ent} for extruded SPS data (data points are means of four observations).

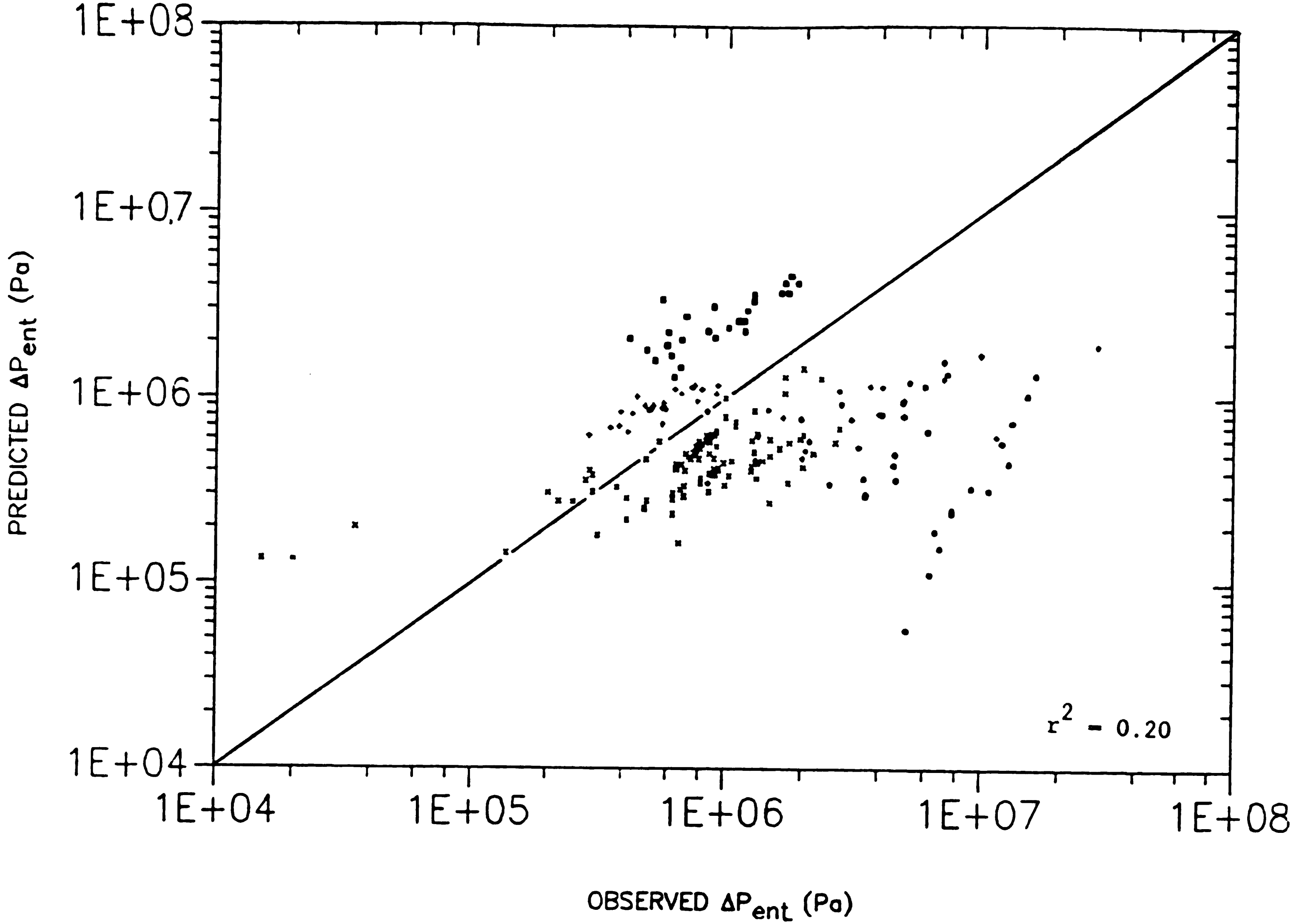


Figure 30. Boger (1982) model predicted vs. observed ΔP_{ent} for all data.

CHAPTER VI.

CONCLUSION

An effective model was successfully developed by means of dimensional analysis and fluid mechanics to predict entrance pressure drop in noncircular multiple hole food extruder dies. The dimensionless parameters significantly effecting the dimensionless entrance pressure drop term (Euler number) are the Reynold's number, Weissenberg number and Rabinowitsch correction factor.

The model form effectively fit published polymer and biological data as well as food dough data collected in this study using a Baker Perkins twin-screw extruder. Food doughs used in this study are potato, defatted soy, and soy polysaccharide.

Future research in extruder die pressure drop modeling should focus on data collection techniques, viscosity prediction models for doughs effected by process history, elasticity measurement, and effects of irregularly shaped die cross-sections on pressure drop.

RECOMMENDATIONS

More data need to be collected on different materials to verify that π_3, π_4, π_6 and π_7 do not contribute to the model. Materials should be non reactive and independent of temperature-time and shear histories so that the ensuing data need not be corrected for these factors. Use of a die with multiple pressure taps may simplify the data collection and increase the accuracy of the measurement of rheological properties. Reasearch needs to be conducted on the feasibility of the use of a multiple pressure tap die for low moisture, high temperature doughs where 'vapor flashing' is likely to occur.

Research needs to be conducted on the effects of work input and shear on the viscosity of extruded materials. A model predicting shear effects can be combined with the generalized model of Morgan et al. (1987) to predict viscosity of screw extruded materials. Further research needs to be conducted for modeling the viscosity of ungelatinized starch doughs.

More research needs to be conducted on eliminating slip, or effectively correcting for error induced by slip. Ramamurthy (1986) concludes that for capillary rheometers, slip can be eliminated by use of a different material other than brass.

Further research needs to be done on the measurement techniques of elasticity of extrudate. The assumption that the elasticity of food materials is much less than that of polymers needs to be verified to ensure that ΔP_{ex} can be neglected for food materials. For further study of ΔP_{ex} for elastic materials, the author recommends review of research done by Han (1976), Pena et al. (1981), and Carreau and Choplin (1985).

Further research needs to be conducted for determining correction factors for calculating die hole pressure drop across irregularly shaped dies. The author recommends review of research done by Lahti (1963), Knudsen and Katz (1958) and Lenk and Fenkel (1981).

After the above proposed research on entrance pressure drop and die hole pressure drop modeling and elasticity measurement, an analysis of the total die pressure predicted vs. observed would be useful to find how accurate the total pressure drop model is. This analysis should demonstrate the ability of the total die pressure drop model to predict pressure drop in scale-up and die modification applications.

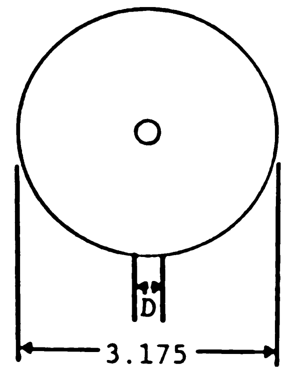
APPENDIX A. CHECK OF INDEPENDENCE OF π TERMS

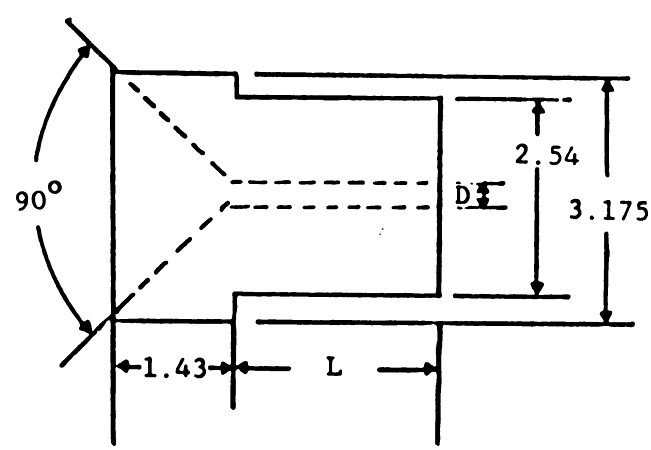
π terms are independent if the number of π terms is equal to the rank (Murphy, 1950) of the following matrix.

	ΔP_{ent}	Q	n_d	r_h	F	D_c	α	m	n	λ	ρ	s
π_1	(1)	~~-2~~	~~2~~	~~4~~							~~-1~~	
π_2		~~1~~	~~-1~~	~~-1~~				~~-1~~			(1)	
π_3			(1)						~~1~~			
π_4					(1)							
π_5									(1)			
π_6			~~1~~	~~2~~		(-2)						
π_7							(1)					
π_8		~~1~~	~~-1~~	~~-3~~						(1)		
π_9												(1)

CHECK: #π TERMS - RANK = 9 - 9 = 0.   OK

APPENDIX B DIE DIMENSIONS (1:1 RATIO)

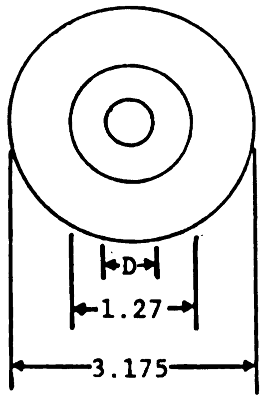


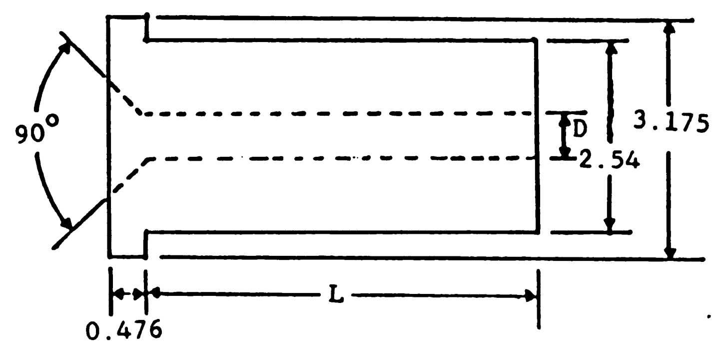


FF DIE

(Dimensions in cm)

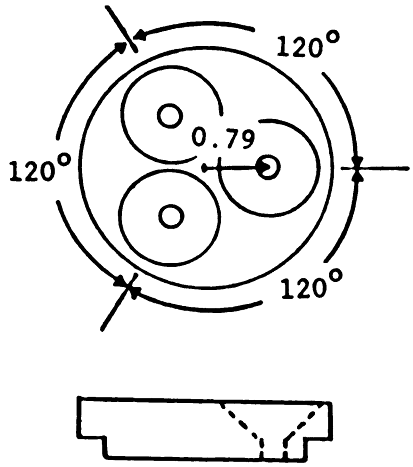
APPENDIX B (Cont'd)

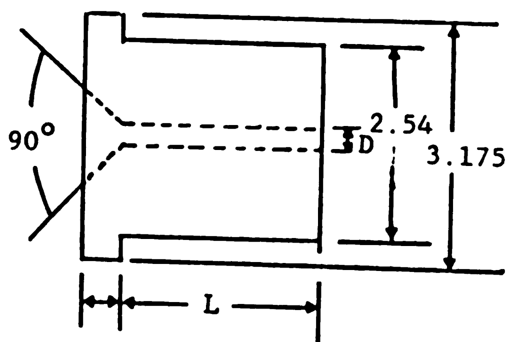




Q DIE
(Dimensions in cm)

APPENDIX B (Cont'd)

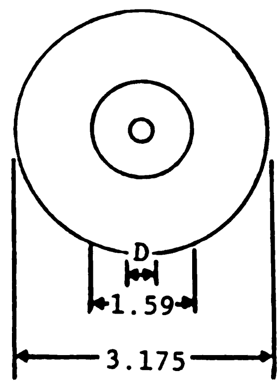


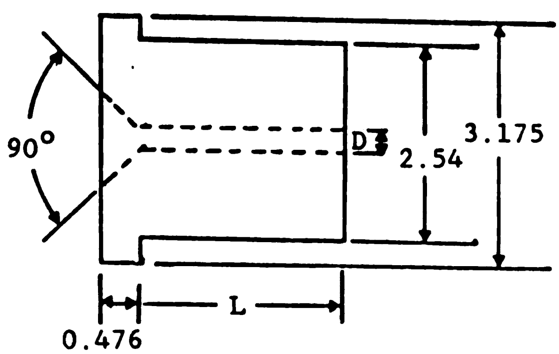


(Cross section per hole)

3H DIE
(Dimensions in cm)

APPENDIX B (Cont'd)





8TH DIE
(Dimensions in cm)

APPENDIX C CAPILLARY RHEOMETER CALCULATIONS

As the material in the CR is pushed out, drag of the material against the CR barrel is decreased. The resulting force-time line measured with the X-Y recorder must be extrapolated to toe force which would be measured when the CR plunger was at the die. For three different velocities per CR loading, extrapolation is accomplished as follows.

Plunger extension-Recorder time Relationship

Figure A shows a schematic of how the CR plunger extension relates to the corresponding time reading (X distance) on the XY recorder (Figure B) for velocities $v_1 < v_2 < v_3$. Relating actual plunger extension to the time (X distance) on the X-Y recorder gives:

$$\frac{y_{d_i}}{y_{a_i}} = \frac{X_{ce_i}}{X_{ct_i}} \quad \text{or} \quad X_{ce_i} = \frac{y_{d_i}}{y_{a_i}} * X_{ct_i}$$

and die force is determined at the time distance of $X_{ct_i} + X_{ce_i}$.

Note: the plotter pen moves at a specified rate, hence time is measured in distance on the Plotter X direction.

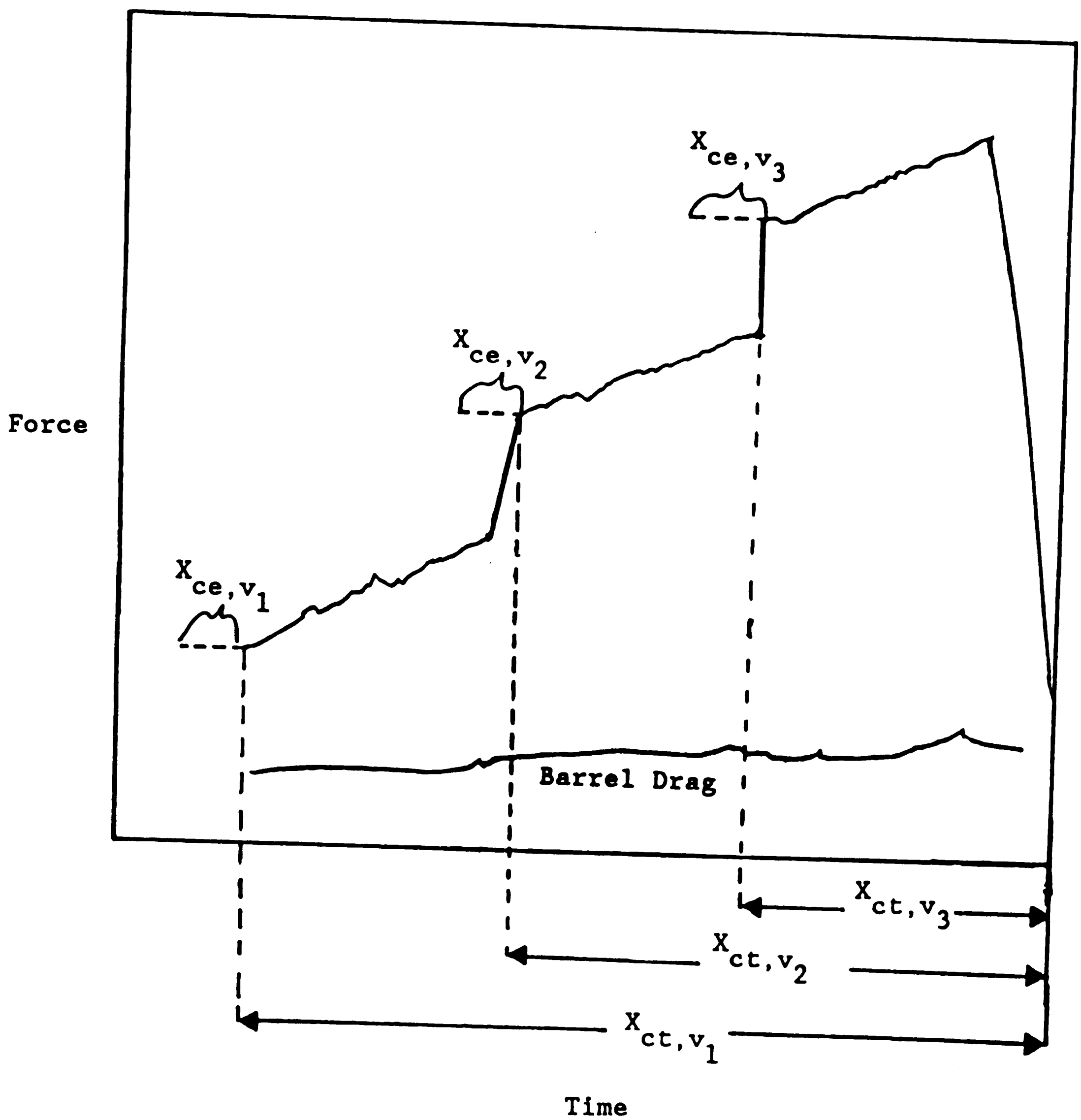


Figure B. Schematic of chart plots where:

$X_{ct,i}$ $(i=v_1, v_2, v_3)$ = X dist. chart pen moved at i mm/min V_{xh}

$X_{ce,i}$ $(i=v_1, v_2, v_3)$ = X extrapolation dist. to point where chart pen would record if plunger went to the die at i mm/min V_{xh}.

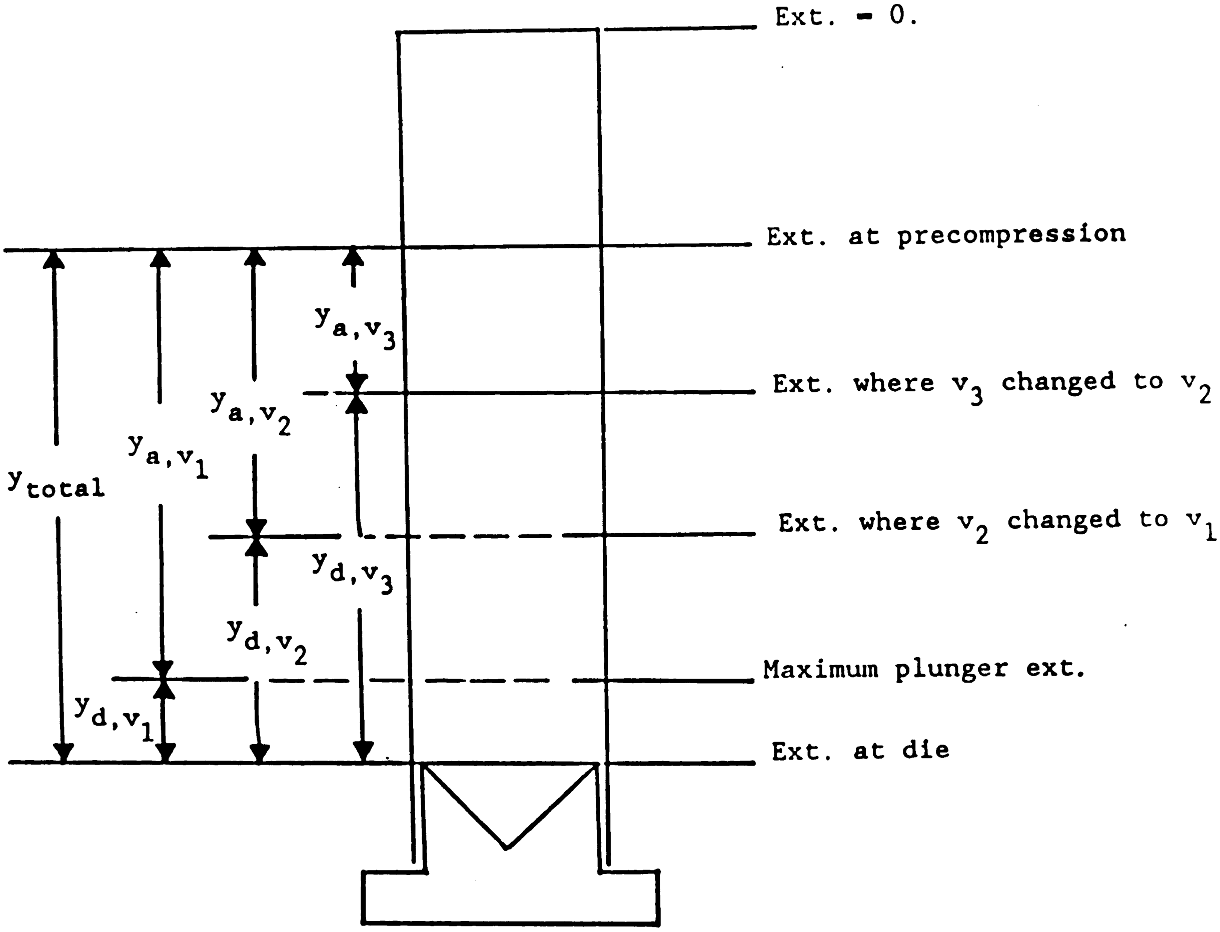


Figure A. Schematic of capillary rheometer extensions where:

y_T (y_{Total}) = (max. ext. - precompres'n ext.) + dist. to die

$y_{a,i}$ ($i=v_1$, v_2, v_3) = y_{actual} at i mm/min crosshead velocity

$y_{d,i}$ ($i=v_1$, v_2, v_3) = distance from die to where V_{xh} was stopped or changed.

APPENDIX C (Cont'd)

Capillary rheometer (CR) Crosshead force- Plotter Y relationship

The Crosshead force (F_{xh}) is related to the plotter y distance measured at the extrapolated time distance minus the plunger drag as follows:

$$\text{Actual Force} = \frac{(\text{Plotter Y - drag})}{(\text{Plotter max. Y})} * \text{CR \% scale} * \text{Load cell maximum}$$

Converting capillary rheometer F_{xh}-V_{xh} to τ_w-Γ.

1. Shear Rate

$$\Gamma = 4\, V_{xh} \frac{R_b^{\,2}}{R_d^{\,3}}$$

2. Shear Stress

$$\tau_w = \frac{(F_{xh_T} - F_{xh_{ent}})\, D_d}{\pi\, D_b^{\,2}\, L}$$

where subscripts b and d refer to capillary rheometer barrel and die diameter respectively.

APPENDIX D FLOUR CALIBRATION PROGRAM

```
C     THIS PROGRAM WILL CALCULATE FEED AND H20 SET FOR SPECIFIED
C     MOISTURE CONTENT AND FEED RATES.(EXTRUDER OPERATIONS!!!)
C
      PROGRAM FLOUR
      INTEGER J,K,M,N,I,W,Z,H,D
      REAL A,B,A1,B1,MC,FLSET,FLRATE,H2OSET,H2ORATE,P,MAX,X,Y,
     +CAPXY,CAPX,CAPY,CAPX2,SUMXY,SUMX2,MEANX,MEANY,FX(10),
     +R2,CAPY2,SUMY2,FY(10),R21,CAPXY1,CAPX1,CAPY1,CAPX21,SUMXY1,
     +SUMX21,MEANX1,MEANY1,AO,STX(10),STY(10),STX1(10),STY1(10)
      OPEN (41,FILE='a:OUTPUT.DTA')
C
9     CONTINUE
      CAPXY=0
      CAPX=0
      CAPY=0
      CAPX2=0
      MEANX=0
      MEANY=0
      CAPY2=0
      I=0
C
C  THE FOLLOWING CALCULATIONS ARE A LINEAR REGRESSION FOR THE FEED
CALIBRATION
C
10    CONTINUE
      WRITE(*,*)'FROM FEED CALIBRATION VALUES, INPUT FLOUR RATE(lb/min)
     +(return) INPUT FLOUR SET(return). WHEN ALL DATA ARE ENTERED,INPUT
     +0.0(return), 0.0(return). INPUT FLOUR SET AS A REAL NUMBER.'
      READ (*,15)X
      READ(*,15)Y
15    FORMAT(F8.4)
      IF (X.EQ.0.0.AND.Y.EQ.0.0)THEN
      GOTO 20
      ELSE
      STX(I+1)=X
      STY(I+1)=Y
16    FORMAT('Feed Points ',2F7.3)
      I=I+1
      FX(I)=LOG(X)
      FY(I)=LOG(Y)
      GOTO 10
      END IF
20    DO 30 L=1,I
      CAPXY=CAPXY+FX(L)*FY(L)
      CAPX=CAPX+FX(L)
      CAPY=CAPY+FY(L)
      CAPX2=CAPX2+FX(L)**2
      CAPY2=CAPY2+FY(L)**2
30    CONTINUE
      SUMXY=CAPXY-(CAPX*CAPY/I)
      SUMX2=CAPX2-(CAPX**2/I)
      SUMY2=CAPY2-(CAPY**2/I)
      B=SUMXY/SUMX2
      MEANX=CAPX/I
      MEANY=CAPY/I
      AO=MEANY-B*MEANX
      A=EXP(AO)
```

APPENDIX D (Cont'd)

```
      R2=SUMXY**2/(SUMX2*SUMY2)
      Write(*,*)'THE REGRESSION R VALUE FOR THE FEED CALIBRATION
     +IS',R2,' IS THIS VALUE ACCEPTABLE?  INPUT 0=NO OR 1=YES
      READ(*,*)H
      IF (H.EQ.0)THEN
      GOTO 9
      END IF
      DO 3 L=1,I
      WRITE(41,16)STX(L),STY(L)
3     CONTINUE
      WRITE(41,44)
34    CONTINUE
      CAPXY1=0
      CAPX1=0
      CAPY1=0
      CAPX21=0
      MEANX1=0
      MEANY1=0
      CAPY21=0
      I=0
C
C THE FOLLOWING CALCULATIONS ARE LINEAR REGRESSION FOR THE H20
CALIBRATION
C
35    CONTINUE
      WRITE(*,*)'FROM H20 CALIBRATION VALUES, INPUT H20 RATE(lb/min),
     +(return), INPUT H20 SET(return). WHEN ALL DATA ARE ENTERED, INPUT
     +0.0(return) ,0.0(return). INPUT H2O SET AS A REAL NUMBER.'
      READ(*,39)X1
      READ(*,39)Y1
39    FORMAT(F9.4)
      IF (X1.EQ.0.0.AND.Y1.EQ.0.0) THEN
      GOTO 40
      ELSE
      STX1(I+1)=X1
      STY1(I+1)=Y1
38    FORMAT('Water Points ',2F7.3)
      I=I+1
      FX(I)=(X1)
      FY(I)=(Y1)
      GOTO 35
      END IF
40    DO 42 L=1,I
      CAPXY1=CAPXY1+FX(L)*FY(L)
      CAPX1=CAPX1+FX(L)
      CAPY1=CAPY1+FY(L)
      CAPX21=CAPX21+FX(L)**2
      CAPY21=CAPY21+FY(L)**2
42    CONTINUE
      SUMXY1=CAPXY1-(CAPX1*CAPY1)/I
      SUMX21=CAPX21-(CAPX1**2/I)
      SUMY21=CAPY21-(CAPY1**2/I)
      B1=SUMXY1/SUMX21
      MEANX1=CAPX1/I
      MEANY1=CAPY1/I
      A1=MEANY1-B1*MEANX1
     R21=SUMXY1**2/(SUMX21*SUMY21)
```

APPENDIX D (Cont'd)

```
      WRITE(*,*)'THE REGRESSION R VALUE FOR H20 CALIBRATION IS'
     +,R21, 'IS THIS VALUE ACCEPTABLE? INPUT 0=NO OR 1=YES.
     +A VALUE ABOVE .99 (99%) IS GENERALLY ACCEPTABLE.'
      READ(*,*)D
      IF(D.EQ.0)THEN
      GOTO 34
      END IF
      DO 4 L=1,I
      WRITE(41,38)STX1(L),STY1(L)
4     CONTINUE
      WRITE(41,44)
      WRITE(41,43)A1,B1,R21
43    FORMAT (5X,'Water regression model "A" is',F8.3,' and'
     +' "B" is',F7.4,' and "R2" is',F6.4)
      WRITE(41,44)
44    FORMAT (' ')
C
C THE FOLLOWING CALCULATES THE FEED AND H20 SET AT DESIRED MC AND FEED
RATE
C
      WRITE (*,*)'Input minimum moisture desired (PERCENT)'
      READ (*,70)J
      WRITE(*,*)'Input maximum moisture desired (PERCENT)'
      READ (*,70)K
      WRITE(*,*)'Input moisture content increment(PERCENT)'
      READ (*,70)Z
      WRITE(*,*)'input minimum feed rate desired (lb/Hr)'
      READ (*,70)M
      WRITE(*,*)'Input maximum feed rate desired (lb/Hr)'
      READ (*,70)N
      WRITE(*,*)'Input feed rate increment(lb/hr)'
      READ(*,70)W
70    FORMAT(I4)
C
      WRITE(41,99)A,B,R2
99    FORMAT(5X,'Feed regression model "A" is',F8.3,' and'
     +' "B" is ',F7.4, ' and "R2" is ',F6.5)
      WRITE(41,101)
101   FORMAT(' ')
      WRITE(41,102)
102   FORMAT(5X,'MC%',4X,'Feed Rate lb/hr',5x,'FEED SET',5X,'H20'
     +' SET')
      DO 140 I=J,K,Z
      WRITE(41,150) I
150   FORMAT(4X,I3)
         DO 160 L=M,N,W
            MC=I/100.0
            P=L/60.0
            FLRATE=(P-(P*MC))/0.92
            H2ORATE=MC*P-(.087*(P-MC*P))
            FLSET=A*FLRATE**B
            H2OSET=A1+(H2ORATE*B1)
            WRITE(41,175)L,FLSET,H2OSET
175         FORMAT(15X,I4,12x,F7.2,7X,F6.2)
160         CONTINUE
140   CONTINUE
      END
```

APPENDIX E DIE SLIP ANALYSIS

Darby (1976) summarizes a method for assessing effects of slip through a coefficient, β', which corrects Γ for a slip velocity. The technique is as follows:

1. Using various tubes of the same length but different radii, Plot $(\Gamma/4\tau_w)$ vs. τ_w for each tube. If $\beta'=0$, these curves should coincide. If not, the curves will be distinct, in which case proceed with step 2.
2. At constant τ_w, plot $(\Gamma/4\tau_w$ vs. $1/R)$ from the curves in step 1. This plot should be linear with a slope = β' for each τ_w.
3. Repeat 2 for various values of τ_w, and then plot β' vs. τ_w to obtain a function $\beta'=f(\tau_w)$. Then all τ_w vs. Γ data should be adjusted by correcting Γ as follows:

$$\Gamma_{\text{no slip}} = \Gamma_{\text{slip measured}} - \frac{4\beta'\tau_w}{R}$$

where τ_w is the measured value. Then τ_w vs. $\Gamma_{\text{no slip}}$ data should be used to obtain τ_w vs. γ data.

APPENDIX F SAS PROGRAM TO COMPUTE CR RHEOLOGICAL PROPERTIES

```
**********************************************************************;
* PROGRAM TO EVALUATE SHEAR STRESS, SHEAR RATE, SLIP;
* FOR SPS RUN ON CAPILLARY RHEOMETER AT MSU;
**********************************************************************;
OPTIONS PS=55 LS=72;
TITLE1     SPS DATA TESTED ON CAPILLARY RHEOMETER AT MSU;
DATA A;
  INFILE ENTRY;
  INPUT NUM MC TEMP L D VXH FXH;
  LD= L/D;
  R=D/2/2.54;
  DINT=INT(D*10000);
  GAMMA=9.1782E-5*VXH/R**3;
*;
* CALCULATING ENTRANCE FORCE AND PRESSURE;
*;
PROC SORT; BY MC TEMP D VXH;
PROC NLIN; BY MC TEMP D VXH;
  PARMS FENT= .05   M=1;
  MODEL FXH=FENT+LD*M;
  OUTPUT OUT=NEW PREDICTED=PFXH PARMS=FENT M;
DATA B;  SET NEW;
  ERROR1=ABS(FXH-PFXH)*100/FXH;
  PENT = 14109.1*FENT;
*;
* CALCULATING TAU;
*;
  TAU = 3527.28*((FXH-FENT)/LD);
  PTAU = 3527.28*((PFXH-FENT)/LD);
  ERROR2=ABS(TAU-PTAU)*100/TAU;
*;
* AVERAGING TAU VALUES;
*;
  PROC SORT; BY MC TEMP D VXH;
  PROC MEANS MAXDEC=1; VAR TAU MC TEMP DINT VXH; BY MC TEMP D VXH;
  OUTPUT OUT=AVE STD=SDEV MEAN=TAUAVE MC1 TEMP1 DINT1 VXH1;
  DATA AVE; SET AVE;
  VXH=VXH1;
  DINT=DINT1;
  TEMP=TEMP1;
  DATA C;
  MERGE AVE B; BY MC TEMP DINT VXH;
  CV= SDEV/TAUAVE*100;
  SLIP= GAMMA/(4*PTAU);
*;
  TAUAVE=INT(10*GAMMA)/10;
  TAU=INT(10*TAU)/10;
  LD=INT(100*LD)/100;
  CV=INT(10*CV)/10;
  OUTPUT;
*;
 PROC SORT; BY MC TEMP D VXH;
 PROC PRINT; VAR MC TEMP D LD GAMMA PENT TAU TAUAVE CV;
```

APPENDIX G SAS PROGRAM TO COMPUTE TSE RHEOLOGICAL PROPERTIES

```
****************************************************************
* PROGRAM TO EVALUATE SHEAR STRESS, SHEAR RATE, PENT, SLIP;
* FOR MATERIALS RUN ON BAKER PERKINS TWIN SCREW EXTRUDER AT MSU;
* ONLY CIRCULAR DIES USED IN TAU - GAMMA ANALYSIS;
* UNITS: KPA, N, M, S, DEG C;
****************************************************************;
OPTIONS LS=80;
TITLE1    DATA TESTED ON BP AT MSU;
DATA A;
   INFILE ENTRY;
   INPUT DIE $ MATL $ LCM DCM ND MC TEMP MDOT PSI TQ RPM;
*;
*  DATA CONVERSION FACTORS AND CONSTANTS;
*;
  IF MATL = 'SPS' THEN TADJ = 2275;
  IF MATL = 'SPS' THEN RHO = 1200;
  IF MATL = 'P' THEN TADJ = 4393;
  IF MATL = 'P' THEN RHO = 1100;
*;
  IF MATL = 'DSF' THEN TADJ=3422;
  IF MATL = 'DSF' THEN RHO=1100;

  PI = 3.141592654;
  PRES = 6.89476*PSI;
  T=5/9*(TEMP-32);
  MASSR = 0.45359/3600*MDOT;
  L = LCM/100;
  D = DCM/100;
  R = D/2;
*;
* CALCULATING GAMMA;
*;
  Q = MASSR/RHO;
  GAMMA = 4*Q/(PI*R**3*ND);
*;
* ADJUSTING PRESSURE FOR TEMPERATURE;
*;
  PROC SORT; BY MC;
  PROC MEANS MAXDEC=1; VAR T; BY MC;
  OUTPUT OUT=C MEAN=TREF;
  DATA D;
  MERGE C A; BY MC;
  IF DIE='21H' THEN DELETE;
  IF DIE='3SLIT' THEN DELETE;
  IF DIE='SLIT' THEN DELETE;
  TINV=(1/(T+273.15));
  TINVR=(1/(TREF+273.15));
  PADJ=PRES*EXP(TADJ*(TINVR-TINV));
*;
* CALCULATING PENT;
*;
  LD=L/D;
  PROC SORT; BY MC DIE GAMMA;
  PROC NLIN; BY MC DIE GAMMA;
  PARMS PENT= 0.05 Z=1;
  MODEL PADJ=PENT+LD*Z;
  OUTPUT OUT=NEW PREDICTED=PPADJ PARMS=PENT Z;
```

APPENDIX G (Cont'd)

```
  DATA E; SET NEW;
  ERROR1=INT(ABS(PADJ-PPADJ)*100/PADJ);
*;
* CALCULATING TAU;
*;
  IF DIE = 'Q' THEN GROUP=1;
  IF DIE = '8TH' THEN GROUP=2;
  IF DIE = '3H' THEN GROUP=3;
  IF DIE = 'FF' THEN GROUP=4;
*;
  TAU = ((PADJ-PENT)/LD);
  SLIP=INT(100*GAMMA/(4*TAU))/100;
*;

  PROC SORT; BY MC GROUP GAMMA;
  PROC MEANS MAXDEC=1; VAR TAU; BY MC GROUP GAMMA;
  OUTPUT OUT=G STD=SDEV MEAN=TAUAVE;
  DATA H;
  MERGE G E; BY MC GROUP GAMMA;
  CV= SDEV/TAUAVE*100;
*;
* COMPUTING M, N;
*;
  IF PENT < 0 THEN DELETE;
  IF DIE='Q' THEN VISC=1;
  IF DIE='8TH' THEN VISC=1;
  IF DIE='3H' THEN VISC=1;
  IF DIE='FF' THEN VISC=1;
  LNGAM=LOG(GAMMA);
  LNTAU=LOG(TAU);
  PROC SORT; BY MC VISC;
  PROC NLIN; BY MC VISC;
  PARMS LNM=100 N=.2;
  MODEL LNTAU=LNM + N*LNGAM;
  OUTPUT OUT=J PREDICTED = PLNTAU PARMS=LNM N STDP=FIT;
  DATA K; SET J;
  N=INT(100*N)/100;
  M=INT (10*(EXP(LNM)/((3*N+1)/(4*N))**N))/10;
  PTAU=INT(LOG(PLNTAU));
  T=INT(10*T)/10;
  LCM=INT(10*LCM)/10;
  TREF=INT(10*TREF)/10;
  PADJ=INT(PADJ);
  PRES=INT(PRES);
  GAMMA=INT(GAMMA);
  TAU=INT(TAU);
  TAUAVE=INT(TAUAVE);
  CV=INT(10*CV)/10;
  PENT=INT(PENT);
  PROC PRINT NOOBS; VAR DIE MATL MC LCM PRES PADJ PENT GAMMA TAU
  TAUAVE CV ERROR1 M N TREF SLIP;
```

APPENDIX H SPS DATA TESTED ON CAPILLARY RHEOMETER

OBS	MC (%)	TEMP (°C)	L (m)	D (m)	VXH (mm/min)	FXH (KN)
1	50	25	0.0254	0.0015875	5	0.32
2	50	25	0.0254	0.0015875	5	0.94
3	50	25	0.0508	0.0015875	5	1.68
4	50	25	0.0508	0.0015875	5	1.68
5	50	25	0.0254	0.0015875	10	1.16
6	50	25	0.0254	0.0015875	10	1.10
7	50	25	0.0508	0.0015875	10	1.96
8	50	25	0.0508	0.0015875	10	2.00
9	50	25	0.0254	0.0015875	50	1.76
10	50	25	0.0254	0.0015875	50	1.48
11	50	25	0.0508	0.0015875	50	3.00
12	50	25	0.0508	0.0015875	50	2.96
13	50	25	0.0254	0.0015875	100	1.66
14	50	25	0.0254	0.0015875	100	2.16
15	50	25	0.0508	0.0015875	100	3.76
16	50	25	0.0508	0.0015875	100	4.60
17	50	25	0.0254	0.0015875	300	2.24
18	50	25	0.0254	0.0015875	300	2.88
19	50	25	0.0508	0.0015875	300	4.20
20	50	25	0.0508	0.0015875	300	4.64
21	50	25	0.0254	0.0015875	500	2.90
22	50	25	0.0254	0.0015875	500	3.28
23	50	25	0.0508	0.0015875	500	4.40
24	50	25	0.0508	0.0015875	500	3.96
25	50	25	0.0254	0.0031750	100	0.54
26	50	25	0.0254	0.0031750	100	0.70
27	50	25	0.0520	0.0031750	100	1.15
28	50	25	0.0520	0.0031750	100	1.17
29	50	25	0.0254	0.0031750	300	0.80
30	50	25	0.0254	0.0031750	300	0.91
31	50	25	0.0520	0.0031750	300	1.53
32	50	25	0.0520	0.0031750	300	1.56
33	50	25	0.0254	0.0031750	500	1.04
34	50	25	0.0254	0.0031750	500	1.14
35	50	25	0.0520	0.0031750	500	1.82
36	50	25	0.0520	0.0031750	500	1.87
37	50	50	0.0254	0.0015875	100	1.10
38	50	50	0.0254	0.0015875	100	1.16
39	50	50	0.0508	0.0015875	100	2.10
40	50	50	0.0508	0.0015875	100	2.02
41	50	50	0.0254	0.0015875	300	1.52
42	50	50	0.0254	0.0015875	300	1.64
43	50	50	0.0508	0.0015875	300	2.88
44	50	50	0.0508	0.0015875	300	2.86
45	50	50	0.0254	0.0015875	500	1.70
46	50	50	0.0254	0.0015875	500	1.96
47	50	50	0.0508	0.0015875	500	3.16
48	50	50	0.0508	0.0015875	500	3.16
49	50	50	0.0254	0.0031750	100	0.40
50	50	50	0.0254	0.0031750	100	0.44

APPENDIX H (Cont'd)

OBS	MC (%)	TEMP (°C)	L (m)	D (m)	VXH (mm/min)	FXH (KN)
51	50	50	0.0520	0.0031750	100	0.74
52	50	50	0.0520	0.0031750	100	0.78
53	50	50	0.0254	0.0031750	300	0.58
54	50	50	0.0254	0.0031750	300	0.52
55	50	50	0.0520	0.0031750	300	0.96
56	50	50	0.0520	0.0031750	300	1.00
57	50	50	0.0254	0.0031750	500	0.58
58	50	50	0.0254	0.0031750	500	0.58
59	50	50	0.0520	0.0031750	500	1.14
60	50	50	0.0520	0.0031750	500	1.16
61	50	70	0.0254	0.0015875	100	0.94
62	50	70	0.0254	0.0015875	100	1.05
63	50	70	0.0508	0.0015875	100	1.64
64	50	70	0.0508	0.0015875	100	0.72
65	50	70	0.0254	0.0015875	300	1.20
66	50	70	0.0254	0.0015875	300	1.36
67	50	70	0.0508	0.0015875	300	2.16
68	50	70	0.0508	0.0015875	300	2.84
69	50	70	0.0254	0.0015875	500	1.48
70	50	70	0.0254	0.0015875	500	1.57
71	50	70	0.0508	0.0015875	500	2.40
72	50	70	0.0508	0.0015875	500	3.00
73	50	70	0.0254	0.0031750	100	0.41
74	50	70	0.0254	0.0031750	100	0.40
75	50	70	0.0520	0.0031750	100	0.63
76	50	70	0.0520	0.0031750	100	0.65
77	50	70	0.0254	0.0031750	300	0.47
78	50	70	0.0254	0.0031750	300	0.47
79	50	70	0.0520	0.0031750	300	0.78
80	50	70	0.0520	0.0031750	300	0.85
81	50	70	0.0254	0.0031750	500	0.53
82	50	70	0.0254	0.0031750	500	0.52
83	50	70	0.0520	0.0031750	500	0.77
84	50	70	0.0520	0.0031750	500	0.89
85	60	25	0.0254	0.0015875	100	0.82
86	60	25	0.0254	0.0015875	100	0.82
87	60	25	0.0508	0.0015875	100	1.40
88	60	25	0.0508	0.0015875	100	1.58
89	60	25	0.0254	0.0015875	300	1.08
90	60	25	0.0254	0.0015875	300	1.08
91	60	25	0.0508	0.0015875	300	1.80
92	60	25	0.0508	0.0015875	300	2.08
93	60	25	0.0254	0.0015875	500	1.18
94	60	25	0.0254	0.0015875	500	1.26
95	60	25	0.0508	0.0015875	500	2.32
96	60	25	0.0508	0.0015875	500	2.48
97	60	25	0.0254	0.0031750	100	0.26
98	60	25	0.0254	0.0031750	100	0.30
99	60	25	0.0520	0.0031750	100	0.48
100	60	25	0.0520	0.0031750	100	0.54

APPENDIX H (Cont'd)

OBS	MC (%)	TEMP (°C)	L (m)	D (m)	VXH (mm/min)	FXH (KN)
101	60	25	0.0254	0.0031750	300	0.36
102	60	25	0.0254	0.0031750	300	0.38
103	60	25	0.0520	0.0031750	300	0.64
104	60	25	0.0520	0.0031750	300	0.68
105	60	25	0.0254	0.0031750	500	0.46
106	60	25	0.0254	0.0031750	500	0.44
107	60	25	0.0520	0.0031750	500	0.74
108	60	25	0.0520	0.0031750	500	0.80
109	70	25	0.0254	0.0015875	100	0.32
110	70	25	0.0254	0.0015875	100	0.24
111	70	25	0.0508	0.0015875	100	0.44
112	70	25	0.0508	0.0015875	100	0.48
113	70	25	0.0254	0.0015875	300	0.38
114	70	25	0.0254	0.0015875	300	0.32
115	70	25	0.0508	0.0015875	300	0.52
116	70	25	0.0508	0.0015875	300	0.56
117	70	25	0.0254	0.0015875	500	0.36
118	70	25	0.0254	0.0015875	500	0.26
119	70	25	0.0508	0.0015875	500	0.58
120	70	25	0.0508	0.0015875	500	0.56
121	70	25	0.0254	0.0031750	100	0.12
122	70	25	0.0254	0.0031750	100	0.10
123	70	25	0.0520	0.0031750	100	0.18
124	70	25	0.0520	0.0031750	100	0.18
125	70	25	0.0254	0.0031750	300	0.16
126	70	25	0.0254	0.0031750	300	0.16
127	70	25	0.0520	0.0031750	300	0.22
128	70	25	0.0520	0.0031750	300	0.24
129	70	25	0.0254	0.0031750	500	0.22
130	70	25	0.0254	0.0031750	500	0.18
131	70	25	0.0520	0.0031750	500	0.26
132	70	25	0.0520	0.0031750	500	0.28
133	70	50	0.0254	0.0015875	100	0.20
134	70	50	0.0254	0.0015875	100	0.22
135	70	50	0.0508	0.0015875	100	0.42
136	70	50	0.0508	0.0015875	100	0.36
137	70	50	0.0254	0.0015875	300	0.30
138	70	50	0.0254	0.0015875	300	0.26
139	70	50	0.0508	0.0015875	300	0.52
140	70	50	0.0508	0.0015875	300	0.46
141	70	50	0.0254	0.0015875	500	0.30
142	70	50	0.0254	0.0015875	500	0.30
143	70	50	0.0508	0.0015875	500	0.62
144	70	50	0.0508	0.0015875	500	0.52
145	70	50	0.0254	0.0031750	100	0.12
146	70	50	0.0254	0.0031750	100	0.12
147	70	50	0.0520	0.0031750	100	0.16
148	70	50	0.0520	0.0031750	100	0.14
149	70	50	0.0254	0.0031750	300	0.12
150	70	50	0.0254	0.0031750	300	0.14

APPENDIX H (Cont'd)

OBS	MC (%)	TEMP (^oC)	L (m)	D (m)	VXH (mm/min)	FXH (KN)
151	70	50	0.0520	0.0031750	300	0.20
152	70	50	0.0520	0.0031750	300	0.20
153	70	50	0.0254	0.0031750	500	0.12
154	70	50	0.0254	0.0031750	500	0.14
155	70	50	0.0520	0.0031750	500	0.18
156	70	50	0.0520	0.0031750	500	0.20
157	70	70	0.0254	0.0015875	100	0.20
158	70	70	0.0254	0.0015875	100	0.20
159	70	70	0.0508	0.0015875	100	0.31
160	70	70	0.0508	0.0015875	100	0.26
161	70	70	0.0254	0.0015875	300	0.22
162	70	70	0.0254	0.0015875	300	0.25
163	70	70	0.0508	0.0015875	300	0.35
164	70	70	0.0508	0.0015875	300	0.33
165	70	70	0.0254	0.0015875	500	0.27
166	70	70	0.0254	0.0015875	500	0.26
167	70	70	0.0508	0.0015875	500	0.36
168	70	70	0.0508	0.0015875	500	0.36
169	70	70	0.0254	0.0031750	100	0.11
170	70	70	0.0254	0.0031750	100	0.12
171	70	70	0.0520	0.0031750	100	0.13
172	70	70	0.0520	0.0031750	100	0.13
173	70	70	0.0254	0.0031750	300	0.09
174	70	70	0.0254	0.0031750	300	0.09
175	70	70	0.0520	0.0031750	300	0.16
176	70	70	0.0520	0.0031750	300	0.13
177	70	70	0.0254	0.0031750	500	0.10
178	70	70	0.0254	0.0031750	500	0.05
179	70	70	0.0520	0.0031750	500	0.14
180	70	70	0.0520	0.0031750	500	0.15

APPENDIX I SPS SHEAR STRESS VS. SHEAR RATE FROM CAPILLARY RHEOMETER

MC (%)	TEMP (^{o}C)	D (cm)	Γ (sec^{-1})	τ_w (KPa)
50	25	0.15875	30	187
50	25	0.15875	150	299.8
50	25	0.15875	902	410
50	25	0.3175	37.6	227
50	25	0.3175	113	290
50	25	0.3175	188	318
50	50	0.15875	301	205
50	50	0.15875	902	284
50	50	0.15875	1504	293
50	50	0.3175	37.6	227
50	50	0.3175	113	290
50	50	0.3175	188	318
50	70	0.15875	301	---
50	70	0.15875	902	269
50	70	0.15875	1504	259
50	70	0.3175	37.6	98.9
50	70	0.3175	113	145
50	70	0.3175	188	128.4
60	25	0.15875	301	39.6
60	25	0.15875	902	41.9
60	25	0.15875	1504	57.3
60	25	0.3175	37.6	96.8
60	25	0.3175	113	122
60	25	0.3175	188	134.7

APPENDIX J   SPS DATA COLLECTED ON TWIN SCREW EXTRUDER

DIE	L (cm)	D (cm)	n_d	MASSR (Kg/S)	MC (%)	T (^oC)	PRES (KPa)	TQ (%)	RPM
FF	2.670	0.3175	2	0.00892	57.0	92.7	6894.7	46	240
FF	2.670	0.3175	2	0.00892	57.2	96.6	6481.0	44	240
FF	0.405	0.3175	2	0.00892	57.8	63.8	3206.0	28	240
FF	0.405	0.3175	2	0.00892	57.6	65.5	3171.5	27	240
FF	2.670	0.3175	2	0.01406	57.3	91.6	7997.9	69	240
FF	2.670	0.3175	2	0.01436	57.6	94.4	7273.9	58	240
FF	0.405	0.3175	2	0.01406	57.8	61.6	3688.6	36	240
FF	0.405	0.3175	2	0.01375	57.2	62.7	3550.8	36	240
FF	2.670	0.3175	2	0.01874	57.9	90.0	7963.4	84	240
FF	2.670	0.3175	2	0.01874	58.6	86.1	7653.1	80	240
FF	0.405	0.3175	2	0.01980	58.9	60.5	3688.6	46	240
FF	0.405	0.3175	2	0.01950	59.0	61.1	3688.6	46	240
Q	0.642	0.6350	2	0.00907	57.9	57.7	1861.5	22	240
Q	0.642	0.6350	2	0.00876	57.6	61.1	1930.5	23	240
Q	2.620	0.6350	2	0.00892	57.0	73.8	3447.3	29	240
Q	2.620	0.6350	2	0.00892	56.5	73.8	3378.4	29	240
Q	0.642	0.6350	2	0.01466	59.3	54.4	2068.4	27	240
Q	0.642	0.6350	2	0.01436	58.5	57.2	2102.9	29	240
Q	2.620	0.6350	2	0.01451	56.8	64.4	3792.1	38	240
Q	2.620	0.6350	2	0.01436	58.1	68.3	3619.7	37	240
Q	0.642	0.6350	2	0.01980	59.4	54.4	2171.8	36	240
Q	0.642	0.6350	2	0.01980	59.0	54.4	2206.3	37	240
Q	2.620	0.6350	2	0.01965	58.3	63.8	3723.1	47	240
Q	2.620	0.6350	2	0.01965	57.9	64.4	3723.1	47	240
RECT	3.180	0.4210	2	0.00892	57.5	85.0	4998.7	37	240
RECT	3.180	0.4210	2	0.00892	57.5	85.5	4929.7	36	240
RECT	0.200	0.4210	2	0.00922	58.3	57.7	1861.5	22	240
RECT	0.200	0.4210	2	0.00907	57.9	58.8	1861.5	24	240
RECT	3.180	0.4210	2	0.01421	58.3	80.5	5757.1	48	240
RECT	3.180	0.4210	2	0.01391	57.5	83.3	5550.2	48	240
RECT	0.200	0.4210	2	0.01421	58.6	55.5	2137.3	24	240
RECT	0.200	0.4210	2	0.01436	58.2	55.5	2068.4	28	240
RECT	3.180	0.4210	2	0.01950	58.9	81.6	5757.1	61	240
RECT	3.180	0.4210	2	0.01965	58.9	77.2	5757.1	61	240
RECT	0.200	0.4210	2	0.01965	59.4	54.4	2137.3	36	240
RECT	0.200	0.4210	2	0.01995	59.7	54.4	2137.3	36	240
3H	0.370	0.3175	6	0.00907	57.0	48.8	2378.6	25	240
3H	0.370	0.3175	6	0.00922	58.0	43.3	2275.2	25	240
3H	2.580	0.3175	6	0.00861	56.0	69.4	5515.8	40	240
3H	2.580	0.3175	6	0.00892	55.8	82.2	5240.0	38	240
3H	0.370	0.3175	6	0.01451	58.4	43.3	2654.4	30	240
3H	0.370	0.3175	6	0.01481	57.0	47.2	2654.4	34	240
3H	2.580	0.3175	6	0.01421	57.4	58.3	6308.7	52	240
3H	2.580	0.3175	6	0.01391	56.0	79.4	5998.4	50	240
3H	0.370	0.3175	6	0.01995	59.0	43.3	2620.0	39	240
3H	0.370	0.3175	6	0.01965	62.5	43.3	2620.0	39	240
3H	2.580	0.3175	6	0.01950	58.7	81.1	6205.2	65	240
3H	2.580	0.3175	6	0.01935	58.5	77.7	6032.9	63	240

APPENDIX J (Cont'd)

DIE	L (cm)	D (cm)	n_d	MASSR (Kg/S)	MC (%)	T (^oC)	PRES (KPa)	TQ (%)	RPM
8TH	2.600	0.3175	2	0.00861	56.4	89.4	6412.1	42	240
8TH	2.600	0.3175	2	0.00892	57.3	96.1	6343.1	42	240
8TH	0.400	0.3175	2	0.00922	58.4	65.5	3033.6	27	240
8TH	0.400	0.3175	2	0.00907	57.7	68.3	3033.6	28	240
8TH	2.600	0.3175	2	0.01391	56.2	97.2	7101.6	58	240
8TH	2.600	0.3175	2	0.01406	58.0	94.4	7032.6	56	240
8TH	0.400	0.3175	2	0.01406	58.6	65.5	3481.8	35	240
8TH	0.400	0.3175	2	0.01406	58.2	66.6	3481.8	45	240
8TH	2.600	0.3175	2	0.01859	57.9	94.4	7446.3	91	240
8TH	2.600	0.3175	2	0.01769	57.9	86.1	7515.2	77	240
8TH	0.400	0.3175	2	0.01935	59.0	60.5	3550.8	44	240
8TH	0.400	0.3175	2	0.01920	59.2	63.8	3619.7	44	240
FF	0.405	0.3175	2	0.00907	63.0	64.4	1896.0	.	350
FF	0.405	0.3175	2	0.00876	63.0	62.7	1930.5	19	350
FF	2.670	0.3175	2	0.00861	63.3	86.1	4274.7	30	350
FF	2.670	0.3175	2	0.00831	63.2	86.1	4274.7	29	350
FF	0.405	0.3175	2	0.01391	66.2	55.5	2171.8	22	350
FF	0.405	0.3175	2	0.01406	61.7	60.0	2137.3	22	350
FF	2.670	0.3175	2	0.01391	63.3	80.0	4964.2	38	350
FF	2.670	0.3175	2	0.01360	63.1	80.0	4688.4	35	350
FF	0.405	0.3175	2	0.01965	64.1	52.7	2206.3	26	350
FF	0.405	0.3175	2	0.01950	64.7	56.1	2206.3	26	350
FF	2.670	0.3175	2	0.01920	64.8	65.5	4860.8	42	350
FF	2.670	0.3175	2	0.01905	64.0	65.5	4895.2	40	350
Q	0.642	0.6350	2	.	64.6	57.2	1034.2	16	350
Q	0.642	0.6350	2	0.00861	64.5	57.2	1068.6	16	350
Q	2.620	0.6350	2	0.00907	63.0	64.4	1896.0	18	350
Q	2.620	0.6350	2	0.00861	61.7	66.6	1930.5	20	350
Q	0.642	0.6350	2	0.01345	63.9	55.0	1172.1	18	350
Q	0.642	0.6350	2	0.01406	64.4	53.8	1172.1	18	350
Q	2.620	0.6350	2	0.01406	64.3	61.1	2240.7	22	350
Q	2.620	0.6350	2	0.01406	64.7	61.1	2137.3	22	350
Q	0.642	0.6350	2	0.01920	64.3	48.8	1172.1	20	350
Q	0.642	0.6350	2	0.01935	64.1	48.3	1206.5	21	350
Q	2.620	0.6350	2	0.01965	65.2	57.7	2275.2	26	350
Q	2.620	0.6350	2	0.01965	65.4	59.4	2275.2	26	350
RECT	0.200	0.4210	2	0.00892	64.2	43.3	1103.1	16	350
RECT	0.200	0.4210	2	0.00952	63.7	38.8	1103.1	16	350
RECT	3.180	0.4210	2	0.00892	63.9	76.6	3240.5	25	350
RECT	3.180	0.4210	2	0.00831	63.5	76.1	3240.5	26	350
RECT	0.200	0.4210	2	0.01391	64.4	46.1	1275.5	18	350
RECT	0.200	0.4210	2	0.01421	65.2	40.0	1172.1	18	350
RECT	3.180	0.4210	2	0.01421	66.2	51.6	3757.6	30	350
RECT	3.180	0.4210	2	0.01406	64.4	68.3	3654.2	29	350
RECT	0.200	0.4210	2	0.01980	65.4	41.6	1275.5	20	350
RECT	0.200	0.4210	2	0.01935	65.7	36.6	1206.5	20	350
RECT	3.18	0.4210	2	0.01950	64.8	58.8	3688.6	34	350
RECT	3.18	0.4210	2	0.01980	64.4	65.0	3688.6	34	350

APPENDIX J (Cont'd)

DIE	L (cm)	D (cm)	n_d	MASSR (Kg/S)	MC (%)	T (^oC)	PRES (KPa)	TQ (%)	RPM
3H	0.37	0.3175	6	0.00892	65.7	52.2	1344.4	17	350
3H	0.37	0.3175	6	0.00922	62.8	53.8	1344.4	17	350
3H	2.58	0.3175	6	0.00876	64.5	73.8	3447.3	26	350
3H	2.58	0.3175	6	0.01043	62.5	75.5	3309.4	26	350
3H	0.37	0.3175	6	0.01436	64.4	46.1	1516.8	.	350
3H	0.37	0.3175	6	0.01406	64.0	50.0	1482.3	20	350
3H	2.58	0.3175	6	0.01421	64.3	69.4	3895.5	31	350
3H	2.58	0.3175	6	0.01421	64.1	68.8	3861.0	30	350
3H	0.37	0.3175	6	0.01950	64.6	43.3	1516.8	22	350
3H	0.37	0.3175	6	0.01950	67.1	40.5	1516.8	22	350
3H	2.58	0.3175	6	0.01980	64.5	67.7	3998.9	45	350
3H	2.58	0.3175	6	0.01950	64.4	67.7	4033.4	46	350
8TH	0.40	0.3175	2	0.00876	64.7	60.5	1689.2	19	350
8TH	0.40	0.3175	2	0.00907	64.8	61.6	1654.7	19	350
8TH	2.60	0.3175	2	0.00876	64.0	83.3	4067.9	29	350
8TH	2.60	0.3175	2	0.00892	65.4	85.0	4136.8	29	350
8TH	0.40	0.3175	2	0.01375	65.2	58.3	2033.9	22	350
8TH	0.40	0.3175	2	0.01391	64.5	58.3	1965.0	22	350
8TH	2.60	0.3175	2	0.01391	63.7	77.2	4619.4	35	350
8TH	2.60	0.3175	2	0.01391	63.5	78.3	4585.0	35	350
8TH	0.40	0.3175	2	0.01905	64.7	56.1	2068.4	25	350
8TH	0.40	0.3175	2	0.01950	62.7	56.1	2033.9	26	350
8TH	2.60	0.3175	2	0.01935	64.6	71.6	4757.3	42	350
8TH	2.60	0.3175	2	0.01935	64.5	70.5	4722.9	41	350

APPENDIX K POTATO DOUGH DATA COLLECTED ON TWIN SCREW EXTRUDER

DIE	L (M)	D (M)	MC (%)	T (°C)	MASSR (KG/S)	PRES (KPa)	TQ (%)	RPM	n_d	β
8TH	0.004	0.003175	50	43.8	0.01259	6205	47	100	2	2.38
8TH	0.004	0.003175	50	67.2	0.01259	2206	34	350	2	2.29
8TH	0.004	0.003175	50	47.2	0.02003	6687	71	100	2	2.16
8TH	0.004	0.003175	50	70.0	0.02003	3309	40	350	2	2.29
8TH	0.015	0.003175	50	56.1	0.00869	4171	26	220	2	2.20
8TH	0.015	0.003175	50	61.1	0.00869	4378	27	220	2	2.36
8TH	0.015	0.003175	50	56.1	0.01259	4757	31	220	2	2.22
8TH	0.015	0.003175	50	60.0	0.01259	4998	32	220	2	2.42
8TH	0.015	0.003175	50	56.1	0.02003	6481	44	220	2	2.00
8TH	0.026	0.003175	50	40.0	0.00869	6825	48	100	2	2.29
8TH	0.026	0.003175	50	58.8	0.00869	3309	35	300	2	2.29
8TH	0.026	0.003175	50	44.4	0.01259	8239	66	100	2	2.15
8TH	0.026	0.003175	50	67.7	0.01259	3930	39	300	2	1.96
8TH	0.026	0.003175	50	56.6	0.02003	8859	75	170	2	2.29
8TH	0.026	0.003175	50	67.7	0.02003	5619	46	300	2	2.29
Q	0.00642	0.006350	50	59.4	0.01259	792	30	350	2	2.04
Q	0.00642	0.006350	50	39.4	0.01259	2620	30	100	2	2.04
Q	0.00642	0.006350	50	60.5	0.02003	1137	36	350	2	.
Q	0.00642	0.006350	50	41.6	0.02003	3068	49	100	2	2.00
Q	0.02600	0.006350	50	70.0	0.00869	3171	26	220	2	1.94
Q	0.02600	0.006350	50	70.0	0.00869	3240	29	220	2	2.06
Q	0.02600	0.006350	50	44.4	0.01259	2551	26	220	2	1.89
Q	0.02600	0.006350	50	58.8	0.01259	3102	31	220	2	1.82
Q	0.02600	0.006350	50	55.5	0.02003	4067	41	220	2	2.00
Q	0.02600	0.006350	50	57.7	0.02003	4067	40	220	2	1.85
Q	0.05200	0.006350	50	28.8	0.00869	2792	26	100	2	1.80
Q	0.05200	0.006350	50	51.6	0.00869	999	26	350	2	1.72
Q	0.05200	0.006350	50	37.7	0.01259	3619	39	100	2	1.99
Q	0.05200	0.006350	50	60.5	0.01259	1413	30	350	2	1.70
Q	0.05200	0.006350	50	41.1	0.02003	4653	56	100	2	1.94
Q	0.05200	0.006350	50	58.8	0.02003	1930	34	350	2	2.00
FF	0.00405	0.003175	50	45.5	0.00869	5826	36	100	2	2.30
FF	0.00405	0.003175	50	58.8	0.00869	4136	26	220	2	2.30
FF	0.00405	0.003175	50	61.1	0.00869	3516	26	220	2	2.41
FF	0.00405	0.003175	50	57.2	0.01259	4343	31	220	2	2.36
FF	0.00405	0.003175	50	58.8	0.01259	4067	32	220	2	2.05
FF	0.00405	0.003175	50	55.0	0.02003	5377	40	220	2	2.36
FF	0.00405	0.003175	50	54.4	0.02003	5584	40	220	2	2.38
FF	0.02670	0.003175	50	57.7	0.00869	3619	32	220	2	2.18
FF	0.02670	0.003175	50	60.0	0.01259	5377	39	220	2	.
FF	0.02670	0.003175	50	58.8	0.01259	5102	39	220	2	2.47
FF	0.02670	0.003175	50	60.0	0.02003	7791	54	220	2	2.29
RECT	0.00200	0.004210	50	53.8	0.00869	1310	23	220	2	.
RECT	0.00200	0.004210	50	52.7	0.01259	2033	27	220	2	.
RECT	0.00200	0.004210	50	51.6	0.01259	1827	27	220	2	.
RECT	0.00200	0.004210	50	47.7	0.02003	2723	34	220	2	.
RECT	0.03180	0.004210	50	61.1	0.00869	2757	26	220	2	.
RECT	0.03180	0.004210	50	56.6	0.01259	3343	33	220	2	.
RECT	0.03180	0.004210	50	57.2	0.01259	3550	31	220	2	.
RECT	0.03180	0.004210	50	55.0	0.02003	5515	42	220	2	.

APPENDIX K (Cont'd)

DIE	L (M)	D (M)	MC (%)	T (^oC)	MASSR (KG/S)	PRES (KPa)	TQ (%)	RPM	n_d	β
3H	0.00370	0.003175	50	53.3	0.00869	2033	28	220	6	.
3H	0.00370	0.003175	50	53.3	0.00869	1689	27	220	6	.
3H	0.00370	0.003175	50	50.0	0.01259	2516	29	220	6	.
3H	0.00370	0.003175	50	48.8	0.01259	2551	29	220	6	.
3H	0.00370	0.003175	50	46.6	0.02003	3792	36	220	6	.
3H	0.02580	0.003175	50	51.6	0.00869	2516	29	220	6	.
3H	0.02580	0.003175	50	53.3	0.01259	3688	30	220	6	.
3H	0.02580	0.003175	50	50.0	0.01259	3757	30	220	6	.
3H	0.02580	0.003175	50	49.4	0.02003	5481	39	220	6	.

APPENDIX L DEFATTED SOY DOUGH DATA COLLECTED ON TWIN SCREW EXTRUDER

DIE	L (cm)	D (cm)	n_d	MC (%)	T (^oC)	MASSR (kg/s)	PRES (KPa)	TQ (%)	RPM
8TH	2.600	0.3175	2	43.5	50.0	0.0184	2275	55	110
8TH	0.400	0.3175	2	43.0	43.3	0.0182	1116	25	110
FF	2.670	0.3175	2	41.1	56.1	0.0196	2323	54	150
FF	0.405	0.3175	2	41.7	50.0	0.0193	1103	35	150
Q	2.620	0.6350	2	38.9	45.5	0.0193	1172	37	150
Q	0.642	0.6350	2	39.2	44.4	0.0188	737	30	150
3H	2.580	0.3175	6	37.7	53.8	0.0190	1999	49	150
3H	0.370	0.3175	6	39.6	42.7	0.0196	861	31	150
RECT	3.180	0.4210	2	41.8	51.6	0.0190	1792	47	150
RECT	0.200	0.4210	2	40.2	47.7	0.0195	792	34	150
8TH	2.600	0.3175	2	41.5	52.2	0.0151	2551	61	150
8TH	0.400	0.3175	2	41.4	46.1	0.0149	1172	37	150
FF	2.670	0.3175	2	38.7	56.6	0.0155	2551	65	150
FF	0.405	0.3175	2	42.1	43.8	0.0151	1172	34	150
Q	2.620	0.6350	2	43.2	43.8	0.0145	1192	36	150
Q	0.642	0.6350	2	38.5	38.8	0.0151	689	30	150
3H	2.580	0.3175	6	40.8	47.7	0.0155	2102	55	150
3H	0.370	0.3175	6	38.5	41.1	0.0157	896	37	150
RECT	3.180	0.4210	2	37.7	43.3	0.0149	2068	50	150
RECT	0.200	0.4210	2	39.3	41.1	0.0158	723	34	150
8TH	2.600	0.3175	2	38.3	53.8	0.0119	2551	60	100
8TH	0.400	0.3175	2	37.4	48.3	0.0120	1275	40	100
FF	2.670	0.3175	2	38.6	51.1	0.0123	2585	61	100
FF	0.405	0.3175	2	39.3	43.3	0.0114	1206	35	100
Q	2.620	0.6350	2	39.3	45.5	0.0131	1378	45	100
Q	0.642	0.6350	2	40.4	41.6	0.0130	792	32	100
3H	2.580	0.3175	6	38.5	55.0	0.0122	2171	51	100
3H	0.370	0.3175	6	38.6	41.6	0.0128	965	31	100
RECT	3.180	0.4210	2	40.2	48.8	0.0122	1723	50	100
RECT	0.200	0.4210	2	38.2	45.0	0.0128	758	29	100
8TH	2.600	0.3175	2	42.7	47.7	0.0093	1792	41	100
8TH	0.400	0.3175	2	41.3	38.3	0.0113	827	26	100
FF	2.670	0.3175	2	41.9	47.7	0.0092	2033	45	100
FF	0.405	0.3175	2	41.5	92.2	0.0102	827	37	100
Q	2.620	0.6350	2	41.7	37.2	0.0102	896	27	100
Q	0.642	0.6350	2	42.4	35.5	0.0108	517	31	100
3H	2.580	0.3175	6	41.5	42.2	0.0101	827	36	100
3H	0.370	0.3175	6	40.3	45.0	0.0114	1447	28	100
RECT	3.180	0.4210	2	42.8	37.2	0.0101	1378	39	100
RECT	0.200	0.4210	2	39.8	36.1	0.0104	551	22	100
8TH	2.600	0.3175	2	38.0	50.0	0.0172	2620	70	120
8TH	0.400	0.3175	2	37.3	43.3	0.0166	1310	42	120
FF	2.670	0.3175	2	38.0	56.1	0.0173	2757	70	120
FF	0.405	0.3175	2	38.8	45.5	0.0172	1344	45	120
Q	2.620	0.6350	2	36.4	44.4	0.0172	1378	46	120
Q	0.642	0.6350	2	38.9	39.4	0.0167	827	32	120
3H	2.580	0.3175	6	38.4	53.3	0.0172	2137	55	120
3H	0.370	0.3175	6	38.4	42.2	0.0172	1034	38	120
RECT	3.180	0.4210	2	38.5	47.7	0.0166	2068	52	120
RECT	0.200	0.4210	2	39.9	42.7	0.0172	861	36	120

APPENDIX M SHEAR RATE AND SHEAR STRESS VALUES FOR EXTRUDED SPS

SPS MC= 58.0%. T= 66.6°C

DIE	Γ (S^{-1})	γ (S^{-1})	τ_w (KPa)
Q	146	245	732
	229	384	645
	313	524	589
8th	1169	1959	1044
	1837	3079	1234
	2506	4200	1195
FF	1169	1959	1130
	1838	3079	1267
	2506	4200	1168
3H	389	652	705
	613	1027	688
	835	1399	891

SPS MC=64.3%, T = 59.3°C

DIE	Γ (S^{-1})	γ (S^{-1})	τ_w (KPa)
Q	146	240	373
	229	376	389
	313	514	415
8th	1169	1920	702
	1838	3020	669 (1)
	2506		587 (1)
FF	1169	1920	704
	1837	3020	716 (1)
	2506		495 (1)

(1) Values excluded from data analysis because of extreme slip

APPENDIX N SHEAR RATE AND SHEAR STRESS VALUES FOR EXTRUDED POTATO DOUGH

DIE	Γ (S^{-1})	γ (S^{-1})	τ_w (KPa)
3H	419	437	68
	607	633	177
	966	1007	255
8th	1257	1311	189
	1822	1900	330
	2900	3024	479
FF	1822	1900	213
	2900	3024	567

APPENDIX P SHEAR RATE AND SHEAR STRESS VALUES FOR EXTRUDED DEFATTED SOY DOUGH

DIE	Γ (S^{-1})	γ (S^{-1})	τ_w (KPa)
Q	187	343	107
	224	411	192
	275	505	180
	308	566	176
	345	634	149
8th	1498	2752	202
	1797	3301	247
	2205	4050	278
	2471	4539	219
	2766	5081	233
3H	599	1100	266
	735	1350	208
	823	1512	220
	922	1694	268
FF	1797	3301	244
	2205	4050	348
	2471	4539	297
	2766	5081	283

APPENDIX Q ENTRANCE PRESSURE DROP DATA FROM LITERATURE

MATL(1)	ρ Kg/m^3	Γ sec^{-1}	ΔP_{ent} KPa	m $KPa\text{-}s^n$	n	$\lambda^{(2)}$ sec	D m	D_c m	α deg
Data of Remsen and Clark (1978)									
S3250	1000	3.00	10679	57.30	0.36	0.000	0.0012	0.009500	90
S3250	1000	7.50	12740	57.30	0.36	0.000	0.0012	0.009500	90
S3250	1000	15.00	11959	57.30	0.36	0.000	0.0012	0.009500	90
S3250	1000	30.00	13146	57.30	0.36	0.000	0.0012	0.009500	90
S3250	1000	75.00	15019	57.30	0.36	0.000	0.0012	0.009500	90
S3250	1000	150.00	16112	57.30	0.36	0.000	0.0012	0.009500	90
Data of Jasberg et al. (1981)									
S30120	1000	300.00	3530	7.45	0.43	0.000	0.0020	0.019050	180
S30120	1000	500.00	3470	7.45	0.43	0.000	0.0020	0.019050	180
S30120	1000	1000.00	4570	7.45	0.43	0.000	0.0020	0.019050	180
S30120	1000	3000.00	4970	7.45	0.43	0.000	0.0020	0.019050	180
S30120	1000	100.00	5100	1.45	0.63	0.000	0.0020	0.019050	180
S30120	1000	300.00	6280	1.45	0.63	0.000	0.0020	0.019050	180
S30120	1000	500.00	6880	1.45	0.63	0.000	0.0010	0.019050	180
S30120	1000	1000.00	7650	1.45	0.63	0.000	0.0010	0.019050	180
S30120	1000	500.00	6570	6.60	0.39	0.000	0.0010	0.019050	180
S30120	1000	1000.00	7650	6.60	0.39	0.000	0.0010	0.019050	180
S30120	1000	2000.00	9120	6.60	0.39	0.000	0.0010	0.019050	180
Data of Morgan (1979)									
S3424	1400	0.95	4070	189.00	0.22	0.000	0.0032	0.015000	90
S3424	1400	1.90	4907	189.00	0.22	0.000	0.0032	0.015000	90
S3424	1400	4.74	5965	189.00	0.22	0.000	0.0032	0.015000	90
S3424	1400	9.48	7289	189.00	0.22	0.000	0.0032	0.015000	90
S3424	1400	19.00	7077	189.00	0.22	0.000	0.0032	0.015000	90
S347160	1400	47.40	3550	28.00	0.26	0.000	0.0032	0.015000	90
S347160	1400	94.80	4610	28.00	0.26	0.000	0.0032	0.015000	90
S347160	1400	190.00	4520	28.00	0.26	0.000	0.0032	0.015000	90
S347160	1400	948.00	6130	28.00	0.26	0.000	0.0032	0.015000	90
Data of Crater and Cuculo (1984)									
PET96265	1360	137.00	410	5.78	0.67	0.004	0.0010	0.009525	45
PET96265	1360	285.00	900	5.78	0.67	0.002	0.0010	0.009525	45
PET96265	1360	150.00	290	5.78	0.67	0.004	0.0010	0.009525	180
PET96265	1360	570.00	1000	5.78	0.67	0.001	0.0010	0.009525	180
PET96265	1360	850.00	1700	5.78	0.67	0.000	0.0010	0.009525	180
PET96265	1360	1000.00	2000	5.78	0.67	0.000	0.0010	0.009525	180
PET72285	1360	150.00	220	5.78	0.67	0.004	0.0010	0.009525	45
PET72285	1360	420.00	660	0.54	0.87	0.009	0.0010	0.009525	45
PET72285	1360	750.00	1500	0.54	0.87	0.005	0.0010	0.009525	45
PET72285	1360	1000.00	1750	0.54	0.87	0.004	0.0010	0.009525	45
PET72285	1360	1250.00	2000	0.54	0.87	0.003	0.0010	0.009525	45
PET72285	1360	300.00	15	0.54	0.87	0.012	0.0010	0.009525	180
PET72285	1360	475.00	35	0.54	0.87	0.008	0.0010	0.009525	180
PET72285	1360	775.00	200	0.54	0.87	0.005	0.0010	0.009525	180
PET72285	1360	1000.00	300	0.54	0.87	0.004	0.0010	0.009525	180
PET72285	1360	1500.00	780	0.54	0.87	0.002	0.0010	0.009525	180
PET72265	1360	150.00	20	2.05	0.71	0.035	0.0010	0.009525	45
PET72265	1360	420.00	250	2.05	0.71	0.017	0.0010	0.009525	45
PET72265	1360	750.00	900	2.05	0.71	0.011	0.0010	0.009525	45
PET72265	1360	1000.00	1300	2.05	0.71	0.009	0.0010	0.009525	45

APPENDIX Q (Cont'd)

MATL[1]	ρ Kg/m^3	Γ sec^{-1}	ΔP_{ent} KPa	m KPa-s^n	n	λ[2] sec	D m	D_c m	α deg
PET72265	1360	1250.00	1500	2.05	0.71	0.007	0.0010	0.009525	45
PET72265	1360	150.00	137	2.05	0.71	0.035	0.0010	0.009525	180
PET72265	1360	475.00	375	2.05	0.71	0.015	0.0010	0.009525	180
PET72265	1360	775.00	490	2.05	0.71	0.011	0.0010	0.009525	180
PET72265	1360	1000.00	790	2.05	0.71	0.009	0.0010	0.009525	180
PET72265	1360	1500.00	1100	2.05	0.71	0.006	0.0010	0.009525	180
PET96285	1360	300.00	280	2.32	0.76	0.019	0.0010	0.009525	180
PET96285	1360	570	550	2.32	0.76	0.001	0.0010	0.009525	180
PET96285	1360	850	1000	2.32	0.76	0.001	0.0010	0.009525	180
PET96285	1360	1250	1700	2.32	0.76	0.000	0.0010	0.009525	180
PET96285	1360	1600	2350	2.32	0.76	0.000	0.0010	0.009525	180
PET96285	1360	285	300	2.12	0.75	0.002	0.0010	0.009525	45
PET96285	1360	855	1100	2.12	0.75	0.000	0.0010	0.009525	45
PET96285	1360	1100	1300	2.12	0.75	0.000	0.0010	0.009525	45
Data of Jasberg et al. (1981)									
PE	915	500	667	11.00	0.33	0.033	0.0010	0.019050	180
PE	915	1000	1260	11.00	0.33	0.026	0.0010	0.019050	180
PE	915	2000	2190	11.00	0.33	0.021	0.0010	0.019050	180
PE	915	3000	2670	11.00	0.33	0.018	0.0020	0.019050	180
PE	915	5000	2770	11.00	0.33	0.015	0.0020	0.019050	180
PE	915	200	314	4.05	0.47	0.071	0.0020	0.019050	180
PE	915	300	412	4.05	0.47	0.058	0.0020	0.019050	180
PE	915	500	494	4.05	0.47	0.046	0.0020	0.019050	180
PE	915	1000	912	4.05	0.47	0.033	0.0020	0.019050	180
Data of Han (1973)									
HDPE	980	125	1034	19.60	0.33	0.044	0.0031	0.019050	15
HDPE	980	180	1268	19.60	0.33	0.039	0.0031	0.019050	15
HDPE	980	260	1495	19.60	0.33	0.034	0.0031	0.019050	15
HDPE	980	340	1630	19.60	0.33	0.031	0.0031	0.019050	15
HDPE	980	430	1767	19.60	0.33	0.029	0.0031	0.019050	15
HDPE	980	490	1950	19.60	0.33	0.028	0.0031	0.019050	15
HDPE	980	575	2007	19.60	0.33	0.026	0.0031	0.019050	15
HDPE	980	150	693	19.60	0.33	0.041	0.0031	0.019050	30
HDPE	980	230	787	19.60	0.33	0.036	0.0031	0.019050	30
HDPE	980	280	863	19.60	0.33	0.033	0.0031	0.019050	30
HDPE	980	370	920	19.60	0.33	0.030	0.0031	0.019050	30
HDPE	980	466	1271	19.60	0.33	0.028	0.0031	0.019050	30
HDPE	980	590	1339	19.60	0.33	0.026	0.0031	0.019050	30
HDPE	980	190	675	19.60	0.33	0.038	0.0031	0.019050	60
HDPE	980	270	765	19.60	0.33	0.034	0.0031	0.019050	60
HDPE	980	340	796	19.60	0.33	0.031	0.0031	0.019050	60
HDPE	980	430	863	19.60	0.33	0.029	0.0031	0.019050	60
HDPE	980	540	878	19.60	0.33	0.027	0.0031	0.019050	60
HDPE	980	625	920	19.60	0.33	0.025	0.0031	0.019050	60
HDPE	980	195	641	19.60	0.33	0.038	0.0031	0.019050	90
HDPE	980	280	701	19.60	0.33	0.033	0.0031	0.019050	90
HDPE	980	360	765	19.60	0.33	0.031	0.0031	0.019050	90
HDPE	980	450	839	19.60	0.33	0.028	0.0031	0.019050	90
HDPE	980	550	839	19.60	0.33	0.026	0.0031	0.019050	90
HDPE	980	650	920	19.60	0.33	0.025	0.0031	0.019050	90
HDPE	980	156	641	19.60	0.33	0.041	0.0031	0.019050	120
HDPE	980	230	730	19.60	0.33	0.036	0.0031	0.019050	120
HDPE	980	295	751	19.60	0.33	0.033	0.0031	0.019050	120

APPENDIX Q (Cont'd)

MATL[(1)]	ρ	Γ	ΔP_{ent}	m	n	$\lambda^{(2)}$	D	D_c	α
	Kg/m^3	sec^{-1}	KPa	$KPa\text{-}s^n$		sec	m	m	deg
HDPE	980	380	778	19.60	0.33	0.030	0.0031	0.019050	120
HDPE	980	450	787	19.60	0.33	0.028	0.0031	0.019050	120
HDPE	980	540	863	19.60	0.33	0.027	0.0031	0.019050	120
HDPE	980	570	878	19.60	0.33	0.026	0.0031	0.019050	120
HDPE	980	170	641	19.60	0.33	0.039	0.0031	0.019050	180
HDPE	980	250	718	19.60	0.33	0.035	0.0031	0.019050	180
HDPE	980	314	765	19.60	0.33	0.032	0.0031	0.019050	180
HDPE	980	400	810	19.60	0.33	0.030	0.0031	0.019050	180
HDPE	980	465	863	19.60	0.33	0.028	0.0031	0.019050	180
HDPE	980	560	904	19.600	0.33	0.026	0.0031	0.01905	180
LDPE	920	80	620	14.765	0.32	0.118	0.0031	0.01905	15
LDPE	920	190	859	14.765	0.32	0.089	0.0031	0.01905	15
LDPE	920	245	995	14.765	0.32	0.082	0.0031	0.01905	15
LDPE	920	330	1330	14.765	0.32	0.075	0.0031	0.01905	15
LDPE	920	590	1340	14.765	0.32	0.062	0.0031	0.01905	15
LDPE	920	640	1395	14.765	0.32	0.061	0.0031	0.01905	15
LDPE	920	145	620	14.765	0.32	0.098	0.0031	0.01905	30
LDPE	920	240	689	14.765	0.32	0.083	0.0031	0.01905	30
LDPE	920	330	798	14.765	0.32	0.075	0.0031	0.01905	30
LDPE	920	390	859	14.765	0.32	0.071	0.0031	0.01905	30
LDPE	920	475	938	14.765	0.32	0.067	0.0031	0.01905	30
LDPE	920	630	1055	14.765	0.32	0.061	0.0031	0.01905	30
LDPE	920	105	482	14.765	0.32	0.108	0.0031	0.01905	60
LDPE	920	180	620	14.765	0.32	0.091	0.0031	0.01905	60
LDPE	920	270	798	14.765	0.32	0.080	0.0031	0.01905	60
LDPE	920	370	891	14.765	0.32	0.072	0.0031	0.01905	60
LDPE	920	440	938	14.765	0.32	0.068	0.0031	0.01905	60
LDPE	920	95	482	14.765	0.32	0.112	0.0031	0.01905	90
LDPE	920	160	689	14.765	0.32	0.095	0.0031	0.01905	90
LDPE	920	590	980	14.765	0.32	0.062	0.0031	0.01905	90

(1) Material Notation

<u>Notation</u>	<u>Material</u> (Table 4)
S3250	Defatted soy dough 32% MC, 50°C
S30120	Defatted soy dough 30% MC, 120°C
S3424	Defatted soy dough 34% MC, 24°C
S347160	Defatted soy dough 34.7% MC, 160°C
PET96265	.96 PE Terephthalate 265°C
PET72285	.72 PE Terephthalate 285°C
PET72265	.72 PE Terephthalate 265°C
PET96285	.96 PE Terephthalate 285°C
PE	Polyethylene
HDPE	High density polyethylene
LDPE	Low density polyethylene

(2) λ computed by Eqn 18.

APPENDIX R EXPERIMENTAL DATA USED IN COMPUTING ENTRANCE PRESSURE DROP

MATL[1]	ρ	Γ	ΔP_{ent}	m	n	λ	DIE	D	D_c	α	n_d	F
	Kg/m^3	sec^{-1}	KPa	$KPa\text{-}s^n$		sec		m	m	deg		
PF	1100	1822	4439	0.501	0.85	0.12	FF	0.0031	0.031750	90	1	1.00
PF	1100	2898	4780	0.501	0.85	0.12	FF	0.0031	0.031750	90	1	1.00
PF	1100	419	1754	0.501	0.85	0.12	3H	0.0031	0.018330	180	3	1.00
PF	1100	607	1979	0.501	0.85	0.12	3H	0.0031	0.018330	180	3	1.00
PF	1100	966	2680	0.501	0.85	0.12	3H	0.0031	0.018330	180	3	1.00
PF	1100	1257	3002	0.501	0.85	0.12	8TH	0.0031	0.031750	180	1	1.00
PF	1100	1822	3624	0.501	0.85	0.12	8TH	0.0031	0.031750	180	1	1.00
PF	1100	2898	5490	0.501	0.85	0.12	8TH	0.0031	0.031750	180	1	1.00
PF	1100	539	1165	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
PF	1100	539	1165	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
PF	1100	781	1669	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
PF	1100	781	1669	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
PF	1100	1243	1927	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
PF	1100	1243	1927	0.501	0.85	0.12	RECT	0.0042	0.031750	180	1	0.45
SCR1	1200	30	3950	86.000	0.21	0.00	CR	0.0015	0.009525	90	1	1.00
SCR1	1200	150	3668	86.000	0.21	0.00	CR	0.0015	0.009525	90	1	1.00
SCR1	1200	902	9876	86.000	0.21	0.00	CR	0.0015	0.009525	90	1	1.00
SCR1	1200	1503	28218	86.000	0.21	0.00	CR	0.0015	0.009525	90	1	1.00
SCR1	1200	37	1472	86.000	0.21	0.00	CR	0.0031	0.009525	90	1	1.00
SCR1	1200	112	2767	86.000	0.21	0.00	CR	0.0031	0.009525	90	1	1.00
SCR1	1200	187	5207	86.000	0.21	0.00	CR	0.0031	0.009525	90	1	1.00
SCR2	1200	300	2821	64.400	0.19	0.00	CR	0.0015	0.009525	90	1	1.00
SCR2	1200	902	4091	64.400	0.19	0.00	CR	0.0015	0.009525	90	1	1.00
SCR2	1200	1503	7054	64.400	0.19	0.00	CR	0.0015	0.009525	90	1	1.00
SCR2	1200	37	1345	64.400	0.19	0.00	CR	0.0031	0.009525	90	1	1.00
SCR2	1200	112	1966	64.400	0.19	0.00	CR	0.0031	0.009525	90	1	1.00
SCR2	1200	187	503	64.400	0.19	0.00	CR	0.0031	0.009525	90	1	1.00
SCR3	1200	300	11428	30.400	0.28	0.00	CR	0.0015	0.009525	90	1	1.00
SCR3	1200	902	846	30.400	0.28	0.00	CR	0.0015	0.009525	90	1	1.00
SCR3	1200	1503	4938	30.400	0.28	0.00	CR	0.0015	0.009525	90	1	1.00
SCR3	1200	37	2548	30.400	0.28	0.00	CR	0.0031	0.009525	90	1	1.00
SCR3	1200	112	1983	30.400	0.28	0.00	CR	0.0031	0.009525	90	1	1.00
SCR3	1200	187	3298	30.400	0.28	0.00	CR	0.0031	0.009525	90	1	1.00
SCR3	1200	187	3298	30.400	0.28	0.00	CR	0.0031	0.009525	90	1	1.00
SCR4	1200	300	2116	32.250	0.25	0.00	CR	0.0015	0.009525	90	1	1.00
SCR4	1200	902	3104	32.250	0.25	0.00	CR	0.0015	0.009525	90	1	1.00
SCR4	1200	1503	564	32.250	0.25	0.00	CR	0.0015	0.009525	90	1	1.00
SCR4	1200	37	851	32.250	0.25	0.00	CR	0.0031	0.009525	90	1	1.00
SCR4	1200	112	1313	32.250	0.25	0.00	CR	0.0031	0.009525	90	1	1.00
SCR4	1200	187	2037	32.250	0.25	0.00	CR	0.0031	0.009525	90	1	1.00
SPS1	1200	501	1206	132.800	0.27	0.00	RECT	0.0042	0.031750	180	1	0.45
SPS1	1200	788	1282	132.800	0.27	0.00	RECT	0.0042	0.031750	180	1	0.45
SPS1	1200	1074	1283	132.800	0.27	0.00	RECT	0.0042	0.031750	180	1	0.45
SPS1	1200	146	900	132.800	0.27	0.00	Q	0.0063	0.031750	180	1	1.00
SPS1	1200	229	1020	132.800	0.27	0.00	Q	0.0063	0.031750	180	1	1.00
SPS1	1200	313	1108	132.800	0.27	0.00	Q	0.0063	0.031750	180	1	1.00
SPS1	1200	1169	1733	132.800	0.27	0.00	8TH	0.0031	0.031750	180	1	1.00
SPS1	1200	1837	1887	132.800	0.27	0.00	8TH	0.0031	0.031750	180	1	1.00
SPS1	1200	2506	1774	132.800	0.27	0.00	8TH	0.0031	0.031750	180	1	1.00
SPS1	1200	389	694	132.8	0.27	0	3H	0.0031	0.01833	180	3	1.00
SPS1	1200	612	891	132.8	0.27	0	3H	0.0031	0.01833	180	3	1.00
SPS1	1200	835	560	132.8	0.27	0	3H	0.0031	0.01833	180	3	1.00
SPS1	1200	1169	1624	132.8	0.27	0	FF	0.0031	0.03175	90	1	1.00
SPS1	1200	1837	1693	132.8	0.27	0	FF	0.0031	0.03175	90	1	1.00

APPENDIX R (Cont'd)

MATL[1]	ρ Kg/m^3	Γ sec^{-1}	ΔP_{ent} KPa	m $KPa\text{-}s^n$	n	λ sec	DIE	D m	D_c m	α deg	n_d	F
SPS1	1200	2506	1789	132.8	0.27	0	FF	0.0031	0.03175	90	1	1.00
SPS2	1200	501	488	76.7	0.28	0	RECT	0.0042	0.03175	180	1	0.45
SPS2	1200	788	668	76.7	0.28	0	RECT	0.0042	0.03175	180	1	0.45
SPS2	1200	1074	592	76.7	0.28	0	RECT	0.0042	0.03175	180	1	0.45
SPS2	1200	146	628	76.7	0.28	0	Q	0.0063	0.03175	180	1	1.00
SPS2	1200	229	664	76.7	0.28	0	Q	0.0063	0.03175	180	1	1.00
SPS2	1200	313	526	76.7	0.28	0	Q	0.0063	0.03175	180	1	1.00
SPS2	1200	1169	848	76.7	0.28	0	8TH	0.0031	0.03175	180	1	1.00
SPS2	1200	1837	1115	76.7	0.28	0	8TH	0.0031	0.03175	180	1	1.00
SPS2	1200	389	610	76.7	0.28	0	3H	0.0031	0.01833	180	3	1.00
SPS2	1200	612	586	76.7	0.28	0	3H	0.0031	0.01833	180	3	1.00
SPS2	1200	835	417	76.7	0.28	0	3H	0.0031	0.01833	180	3	1.00
SPS2	1200	1169	1186	76.7	0.28	0	FF	0.0031	0.03175	90	1	1.00
SPS2	1200	1837	1171	76.7	0.28	0	FF	0.0031	0.03175	90	1	1.00
DSF	1100	642	386	40.8	0.23	0	RECT	0.0042	0.03175	180	1	0.45
DSF	1100	770	583	40.8	0.23	0	RECT	0.0042	0.03175	180	1	0.45
DSF	1100	945	520	40.8	0.23	0	RECT	0.0042	0.03175	180	1	0.45
DSF	1100	1060	573	40.8	0.23	0	RECT	0.0042	0.03175	180	1	0.45
DSF	1100	1186	773	40.8	0.23	0	RECT	0.0042	0.03175	180	1	0.45
DSF	1100	187	289	40.8	0.23	0	Q	0.0063	0.03175	180	1	1.00
DSF	1100	224	414	40.8	0.23	0	Q	0.0063	0.03175	180	1	1.00
DSF	1100	275	350	40.8	0.23	0	Q	0.0063	0.03175	180	1	1.00
DSF	1100	308	381	40.8	0.23	0	Q	0.0063	0.03175	180	1	1.00
DSF	1100	345	567	40.8	0.23	0	Q	0.0063	0.03175	180	1	1.00
DSF	1100	1498	448	40.8	0.23	0	8TH	0.0031	0.03175	180	1	1.00
DSF	1100	1797	916	40.8	0.23	0	8TH	0.0031	0.03175	180	1	1.00
DSF	1100	2205	810	40.8	0.23	0	8TH	0.0031	0.03175	180	1	1.00
DSF	1100	2471	737	40.8	0.23	0	8TH	0.0031	0.03175	180	1	1.00
DSF	1100	2766	753	40.8	0.23	0	8TH	0.0031	0.03175	180	1	1.00
DSF	1100	499	1672	40.8	0.23	0	3H	0.0031	0.01833	180	3	1.00
DSF	1100	599	431	40.8	0.23	0	3H	0.0031	0.01833	180	3	1.00
DSF	1100	735	505	40.8	0.23	0	3H	0.0031	0.01833	180	3	1.00
DSF	1100	823	513	40.8	0.23	0	3H	0.0031	0.01833	180	3	1.00
DSF	1100	922	481	40.8	0.23	0	3H	0.0031	0.01833	180	3	1.00
DSF	1100	1797	669	40.8	0.23	0	FF	0.0031	0.03175	90	1	1.00
DSF	1100	2205	633	40.8	0.23	0	FF	0.0031	0.03175	90	1	1.00
DSF	1100	2471	742	40.8	0.23	0	FF	0.0031	0.03175	90	1	1.00
DSF	1100	2766	932	40.8	0.23	0	FF	0.0031	0.03175	90	1	1.00

(1) Material Notation

Notation	Material
DSF	Defatted soy dough
PF	Potato dough
SPS1	Extruded SPS 58% MC
SPS2	Extruded SPS 64.3% MC
SCR1	SPS from capillary rheometer 50% MC, 25°C
SCR2	SPS from capillary rheometer 50% MC, 50°C
SCR3	SPS from capillary rheometer 50% MC, 70°C
SCR4	SPS from capillary rheometer 60% MC, 25°C

APPENDIX S SAS PROGRAM FOR COMPUTING ENTRANCE PRESSURE

```
OPTIONS LS =72;
DATA A;
INFILE SET1;
INPUT OBS DIE $ D ND F DSUBC ALPHA C NC;
*;
INFILE SET2;
INPUT OBS MATL $ RHO GAMMA PENT M N LAMDA;
*;
* SETTING TYPE;
*;
  IF MATL='A' THEN TYPE='BIO';
  IF MATL='B' THEN TYPE='BIO';
  IF MATL='C' THEN TYPE='BIO';
  IF MATL='D' THEN TYPE='BIO';
  IF MATL='I' THEN TYPE='POLY';
  IF MATL='J' THEN TYPE='POLY';
  IF MATL='K' THEN TYPE='POLY';
  IF MATL='L' THEN TYPE='POLY';
  IF MATL='M' THEN TYPE='POLY';
  IF MATL='N' THEN TYPE='POLY';
  IF MATL='O' THEN TYPE='POLY';
  IF MATL = 'SCR1' THEN TYPE = 'CR';
  IF MATL = 'SCR2' THEN TYPE = 'CR';
  IF MATL = 'SCR3' THEN TYPE = 'CR';
  IF MATL = 'SCR4' THEN TYPE = 'CR';
  IF MATL = 'DSF' THEN TYPE = 'TSE';
  IF MATL = 'SPS1' THEN TYPE = 'TSE';
  IF MATL = 'SPS2' THEN TYPE = 'TSE';
  IF MATL = 'PF' THEN TYPE = 'TSE';
*;
* SETTING GROUP, BY POLYMER AND BIO AND LITERATURE;
*;
* CALCULATING PI TERMS;
*;
  PROC SORT; BY TYPE;
DATA C; SET A;
  PI = 3.1415926;
  RH = D/4;
  Q=2*ND*PI*(RH**3)*GAMMA;
  PI1=((16*ND**2*(RH**4)*PENT)/(Q**2))/RHO;
  PI2=((RHO*Q)/(RH*ND*PI*M*((GAMMA*(3*N+1)/(4*N))**(N-1))));
  PI3=ND;
  PI4=F;
  PI5=(3*N+1)/(4*N);
  PI6=(16*ND*(RH**2))/(DSUBC**2);
  PI7=ALPHA;
  PI8 = 1+((LAMDA*Q)/(16*ND*(RH**3)*PI));
  LNPI1=LOG(PI1);
  LNPI2=LOG(PI2);
  LNPI3=LOG(PI3);
  LNPI4=LOG(PI4);
  LNPI5=LOG(PI5);
  LNPI6=LOG(PI6);
  LNPI7=LOG(PI7);
  LNPI8=LOG(PI8);
```

APPENDIX S (Cont'd)

```
  REGEN=RHO*(D**N)*(Q/(4*PI*RH**2))**(2-N)/(8**(N-1)*M*((3*N+1)/
  (4*N))**N);
  DPEBOGER=(2*M*((3*N+1)/(4*N)*GAMMA)**N)*(REGEN*(C+1)/32+NC);
  ERBOGER = INT(DPEBOGER-PENT)/PENT*100;
  BOGER2 = (2*M*((3*N+1)/(4*N)*GAMMA)**N)*(PI2*(C+1)/32+NC);
  ERBOG2 = INT(BOGER2-PENT)/PENT*100;
*;
* RESULTS;
*;
  DP = INT(10000*D)/10000;
  MP = INT(10*M)/10;
  NP = INT(100*N)/100;
  DSUBCP = INT(10000*DSUBC)/10000;
  CP = INT(100*C)/100;
  NCP = INT(100*NC)/100;
* PROC PRINT  VAR DIE  MATL MP NP GAMMA PENT DSUBCP
  PI1 PI2 PI3 PI4 PI5 PI6 PI7 PI8;
* PROC SORT  BY TYPE;
* PROC PRINT NOOBS   VAR PENT DPEBOGER; BY TYPE;
*;
* PROC SORT  BY MATL;
* PROC STEPWISE;
* MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8 / FORWARD;
* BY MATL;
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8 / FORWARD;
  DATA D; SET C;
  IF TYPE = 'BIO' OR TYPE = 'POL';
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8/ FORWARD;
  DATA E; SET C;
  IF TYPE = 'POL';
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8/ FORWARD;
  DATA F; SET C;
  IF TYPE = 'BIO';
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8/ FORWARD;
  DATA G; SET C;
  IF TYPE = 'BIO' OR TYPE = 'TSE' OR TYPE = 'CR';
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8/ FORWARD;
  DATA H; SET C;
  IF TYPE = 'TSE' OR TYPE = 'CR';
  PROC STEPWISE;
  MODEL LNPI1 = LNPI2  LNPI3 LNPI4 LNPI5 LNPI6 LNPI7 LNPI8/ FORWARD;
```

APPENDIX T ANOVA TABLES FOR STEPWISE FORWARD REGRESSION OF EQN. 27

ALL DATA

R SQUARE = 0.88396866
C(P) = 6.20601691

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	6	1847.32066661	307.88677777	269.18	0.0001
ERROR	212	242.48268767	1.14378626		
TOTAL	218	2089.80335428			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	-1.15291711				
LNPI2	-1.18510846	0.03445667	1353.05166763	1182.96	0.0001
LNPI3	-0.63247944	0.27702512	5.96210200	5.21	0.0234
LNPI4	0.65345676	0.35453874	3.88553834	3.40	0.0667
LNPI5	2.58675358	0.52345861	27.93124478	24.42	0.0001
LNPI6	-0.14334317	0.12635054	1.47212506	1.29	0.2579
LNPI8	0.58449073	0.11498918	29.55195233	25.84	0.0001

BOUNDS ON CONDITION NUMBER: 2.075972, 53.89638

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.8595	0.8595	40.6669	1327.9560	0.0001
2	LNPI5	2	0.0052	0.8648	33.1423	8.3583	0.0042
3	LNPI8	3	0.0136	0.8784	10.4135	24.0124	0.0001
4	LNPI3	4	0.0030	0.8813	6.9733	5.3906	0.0212
5	LNPI4	5	0.0019	0.8833	5.4883	3.4934	0.0630
6	LNPI6	6	0.0007	0.8840	6.2060	1.2871	0.2579

APPENDIX T (Cont'd)

ALL LITERATURE DATA.

R SQUARE = 0.92795738
C(P) = 6.00000000

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	5	1125.86994782	225.17398956	311.71	0.0001
ERROR	121	87.40769636	0.72237766		
TOTAL	126	1213.27764418			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	-2.62087454				
LNPI2	-0.96834290	0.03779762	474.12595877	656.34	0.0001
LNPI5	7.74400372	0.63844103	106.28055773	147.13	0.0001
LNPI6	-1.00395201	0.15834837	29.03775237	40.20	0.0001
LNPI7	-0.20085608	0.10642614	2.57298736	3.56	0.0615
LNPI8	-0.95693069	0.18975320	18.37160278	25.43	0.0001

BOUNDS ON CONDITION NUMBER: 2.0053, 44.42087

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.8387	0.8387	147.956	649.8326	0.0001
2	LNPI5	2	0.0493	0.8880	67.188	54.5367	0.0001
3	LNPI6	3	0.0244	0.9124	28.150	34.3030	0.0001
4	LNPI8	4	0.0134	0.9258	7.562	22.1237	0.0001
5	LNPI7	5	0.0021	0.9280	6.000	3.5618	0.0615

APPENDIX T (Cont'd)

POLYMER DATA FROM LITERATURE.

R SQUARE = 0.81814085
C(P) = 6.00000000

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	5	96.20570016	19.24114003	85.48	0.0001
ERROR	95	21.38493250	0.22510455		
TOTAL	100	117.59063266			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	1.62856536				
LNPI2	-0.76301681	0.06124559	34.93839022	155.21	0.0001
LNPI5	4.30005273	0.59462695	11.77179430	52.29	0.0001
LNPI6	-0.49140581	0.13720729	2.88742366	12.83	0.0005
LNPI7	-0.32227736	0.06304277	5.88265388	26.13	0.0001
LNPI8	-0.22787577	0.20811843	0.26987305	1.20	0.2763

BOUNDS ON CONDITION NUMBER: 4.6443, 77.87777

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.5777	0.5777	123.595	135.4384	0.0001
2	LNPI5	2	0.1831	0.7608	29.968	74.9902	0.0001
3	LNPI7	3	0.0320	0.7928	15.242	14.9894	0.0002
4	LNPI6	4	0.0231	0.8158	5.199	12.0179	0.0008
5	LNPI8	5	0.0023	0.8181	6.000	1.1989	0.2763

APPENDIX T (Cont'd)

DEFATTED SOY DATA FROM LITERATURE. R SQUARE = 0.99252496
C(P) = 5.00000000

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	4	490.16839969	122.54209992	697.09	0.0001
ERROR	21	3.69162571	0.17579170		
TOTAL	25	493.86002541			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	9.86852899				
LNPI2	-1.01074225	0.02726333	241.61357709	1374.43	0.0001
LNPI5	-2.70569296	0.88659883	1.63719754	9.31	0.0061
LNPI6	-0.23503598	0.16563993	0.35394598	2.01	0.1706
LNPI7	-1.23594343	0.54766675	0.89528808	5.09	0.0348

BOUNDS ON CONDITION NUMBER: 5.202306, 57.76826

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.9850	0.9850	20.1788	1574.5365	0.0001
2	LNPI5	2	0.0057	0.9907	6.1481	14.1007	0.0010
3	LNPI7	3	0.0011	0.9918	5.0134	2.9966	0.0974
4	LNPI6	4	0.0007	0.9925	5.0000	2.0134	0.1706

APPENDIX T (Cont'd)

ALL FOOD MATERIALS FROM LITERATURE AND FROM THIS STUDY.

R SQUARE = 0.95124048
C(P) = 6.00108358

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	6	1872.01012471	312.00168745	360.91	0.0001
ERROR	111	95.95713623	0.86447870		
TOTAL	117	1967.96726094			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	10.55962959				
LNPI2	-1.13463792	0.03237008	1062.13903934	1228.65	0.0001
LNPI3	-0.63629414	0.27282291	4.70227992	5.44	0.0215
LNPI4	0.74751392	0.35972045	3.73303974	4.32	0.0400
LNPI5	-4.66337204	0.77472304	31.32286511	36.23	0.0001
LNPI7	-1.38251886	0.35535902	13.08463879	15.14	0.0002
LNPI8	-0.44582534	0.16107995	6.62217724	7.66	0.0066

BOUNDS ON CONDITION NUMBER: 3.16159, 74.59625

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.9194	0.9194	67.8299	1323.2303	0.0001
2	LNPI5	2	0.0107	0.9301	45.5978	17.6823	0.0001
3	LNPI7	3	0.0122	0.9424	19.9986	24.2026	0.0001
4	LNPI8	4	0.0056	0.9480	9.3080	12.2245	0.0007
5	LNPI3	5	0.0013	0.9493	8.2805	2.9672	0.0877
6	LNPI4	6	0.0019	0.9512	6.0011	4.3183	0.0400

APPENDIX T (Cont'd)

ALL EXPERIMENTAL DATA FROM THIS STUDY. R SQUARE = 0.92245772
C(P) = 6.02234466

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	6	554.75600765	92.45933461	168.53	0.0001
ERROR	85	46.63307856	0.54862445		
TOTAL	91	601.38908621			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	9.29396825				
LNPI2	-1.03148925	0.06433050	141.04921679	257.10	0.0001
LNPI3	-0.17633655	0.21540245	0.36767030	0.67	0.4153
LNPI5	1.99315994	1.12223617	1.73057702	3.15	0.0793
LNPI6	0.44738397	0.15906953	4.33972287	7.91	0.0061
LNPI7	-1.50476378	0.27897226	15.96209124	29.09	0.0001
LNPI8	0.78177762	0.21072830	7.55085074	13.76	0.0004

BOUNDS ON CONDITION NUMBER: 8.406162, 146.2706

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.8450	0.8450	79.9200	490.7595	0.0001
2	LNPI7	2	0.0398	0.8848	38.7807	30.7692	0.0001
3	LNPI8	3	0.0259	0.9108	12.6768	25.5815	0.0001
4	LNPI6	4	0.0079	0.9187	6.1344	8.4324	0.0047
5	LNPI5	5	0.0032	0.9218	4.6848	3.5032	0.0646
6	LNPI3	6	0.0006	0.9225	6.0223	0.6702	0.4153

APPENDIX T (Cont'd)

TWIN-SCREW EXTRUDER DATA FROM THIS STUDY.

R SQUARE = 0.88067270
C(P) = 2.43212636

	DF	SUM OF SQUARES	MEAN SQUARE	F	PROB>F
REGRESSION	4	72.89368395	18.22342099	112.55	0.0001
ERROR	61	9.87677552	0.16191435		
TOTAL	65	82.77045947			

	B VALUE	STD ERROR	TYPE II SS	F	PROB>F
INTERCEPT	4.35474983				
LNPI2	-0.69619258	0.05759814	23.65523535	146.10	0.0001
LNPI4	0.15010593	0.14527829	0.17285406	1.07	0.3056
LNPI6	0.46141609	0.13043597	2.02617077	12.51	0.0008
LNPI8	0.42889568	0.04323441	15.93417582	98.41	0.0001

BOUNDS ON CONDITION NUMBER: 2.037436, 24.53229

NO OTHER VARIABLES MET THE 0.5000 SIGNIFICANCE LEVEL FOR ENTRY

SUMMARY OF FORWARD SELECTION PROCEDURE FOR DEPENDENT VARIABLE LNPI1

STEP	VARIABLE ENTERED	NUMBER IN	PARTIAL R**2	MODEL R**2	C(P)	F	PROB>F
1	LNPI2	1	0.6679	0.6679	100.641	128.6906	0.0001
2	LNPI8	2	0.1866	0.8545	11.267	80.7752	0.0001
3	LNPI6	3	0.0241	0.8786	1.455	12.3178	0.0008
4	LNPI4	4	0.0021	0.8807	2.432	1.0676	0.3056

APPENDIX U ANOVA TABLES FOR LINEAR REGRESSION

1. Regression of Eqn. 27 for published polymer data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	5	96.20570016	19.24114003	85.476	0.0001
ERROR	95	21.38493250	0.22510455		
C TOTAL	100	117.59063			

ROOT MSE	0.4744518	R-SQUARE	0.8181
DEP MEAN	8.719047	ADJ R-SQ	0.8086
C.V.	5.441556		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	1	1.62856536	0.72915465	2.233	0.0279
LNPI2	1	-0.76301681	0.06124559	-12.458	0.0001
LNPI3	0	0	.	.	.
LNPI4	0	0	.	.	.
LNPI5	1	4.30005273	0.59462695	7.232	0.0001
LNPI6	1	-0.49140581	0.13720729	-3.581	0.0005
LNPI7	1	-0.32227736	0.06304277	-5.112	0.0001
LNPI8	1	-0.22787577	0.20811843	-1.095	0.2763

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	1.02154E+14	1.02154E+14	1310.994	0.0001
ERROR	100	7.79213E+12	77921282947		
U TOTAL	101	1.09946E+14			

ROOT MSE	279143.8	R-SQUARE	0.9291
DEP MEAN	905353.4	ADJ R-SQ	0.9284
C.V.	30.83258		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	0.92588020	0.02557140	36.208	0.0001

APPENDIX U (Cont'd)

1. Regression of Eqn. 27 for published defatted soy dough data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	4	490.16840	122.54210	697.087	0.0001
ERROR	21	3.69162571	0.17579170		
C TOTAL	25	493.86003			

ROOT MSE	0.4192752	R-SQUARE	0.9925
DEP MEAN	14.11403	ADJ R-SQ	0.9911
C.V.	2.970626		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	1	9.86852899	2.66071388	3.709	0.0013
LNPI2	1	-1.01074225	0.02726333	-37.073	0.0001
LNPI3	0	0	.	.	.
LNPI4	0	0	.	.	.
LNPI5	1	-2.70569296	0.88659883	-3.052	0.0061
LNPI6	1	-0.23503598	0.16563993	-1.419	0.1706
LNPI7	1	-1.23594343	0.54766675	-2.257	0.0348
LNPI8	0	0	.	.	.

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	2.41589E+15	2.41589E+15	213.294	0.0001
ERROR	25	2.83164E+14	1.13266E+13		
U TOTAL	26	2.69906E+15			

ROOT MSE	3365498	R-SQUARE	0.8951
DEP MEAN	8234025	ADJ R-SQ	0.8909
C.V.	40.87306		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	1.16667834	0.07988436	14.605	0.0001

APPENDIX U (Cont'd)

1. Regression of Eqn. 27 for twin-screw extruder data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	7	72.96672622	10.42381803	61.668	0.0001
ERROR	58	9.80373325	0.16902988		
C TOTAL	65	82.77045947			

ROOT MSE	0.4111324	R-SQUARE	0.8816
DEP MEAN	6.229246	ADJ R-SQ	0.8673
C.V.	6.600035		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	1	4.82881873	1.93533238	2.495	0.0155
LNPI2	1	-0.66693893	0.07417413	-8.992	0.0001
LNPI3	1	-0.01294504	0.13871981	-0.093	0.9260
LNPI4	1	0.19065828	0.17607393	1.083	0.2834
LNPI5	1	-0.67566395	1.04673791	-0.645	0.5212
LNPI6	1	0.48817136	0.16286907	2.997	0.0040
LNPI7	1	0.03216432	0.24319444	0.132	0.8952
LNPI8	1	0.30976205	0.18932755	1.636	0.1072

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	2.24368E+14	2.24368E+14	597.170	0.0001
ERROR	65	2.44217E+13	375718726972		
U TOTAL	66	2.48790E+14			

ROOT MSE	612959	R-SQUARE	0.9018
DEP MEAN	1317796	ADJ R-SQ	0.9003
C.V.	46.51395		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	1.14325345	0.04678359	24.437	0.0001

APPENDIX U (Cont'd)

1. Regression of Eqn. 27 for twin screw extruded potato dough data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	5	8.74900592	1.74980118	232.014	0.0001
ERROR	8	0.06033439	0.007541799		
C TOTAL	13	8.80934032			

ROOT MSE	0.08684353	R-SQUARE	0.9932
DEP MEAN	6.86524	ADJ R-SQ	0.9889
C.V.	1.264974		

NOTE: MODEL IS NOT FULL RANK. LEAST SQUARES SOLUTIONS FOR THE PARAMETERS ARE NOT UNIQUE. SOME STATISTICS WILL BE MISLEADING. A REPORTED DF OF 0 OR B MEANS THAT THE ESTIMATE IS BIASED. THE FOLLOWING PARAMETERS HAVE BEEN SET TO 0, SINCE THE VARIABLES ARE A LINEAR COMBINATION OF OTHER VARIABLES AS SHOWN.

LNPI5 =+.0418519*INTERCEP

LNPI6 =-4.60517*INTERCEP+1.00009*LNPI3 -.713909*LNPI4

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	B	2.01025290	18.80823535	0.107	0.9175
LNPI2	1	-1.20371941	2.24960210	-0.535	0.6071
LNPI3	B	0.009700634	0.09660354	0.100	0.9225
LNPI4	B	0.40792679	1.64483735	0.248	0.8104
LNPI5	0	0	.	.	.
LNPI6	0	0	.	.	.
LNPI7	1	-0.07077102	0.11879876	-0.596	0.5678
LNPI8	1	-0.04989444	2.76469565	-0.018	0.9860

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	1.22635E+14	1.22635E+14	2127.529	0.0001
ERROR	13	749343593639	57641814895		
U TOTAL	14	1.23384E+14			

ROOT MSE	240087.1	R-SQUARE	0.9939
DEP MEAN	2655886	ADJ R-SQ	0.9935
C.V.	9.039813		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	0.99158004	0.02149760	46.125	0.0001

APPENDIX U (Cont'd)

1. Regression of Eqn. 27 for twin screw extruder defatted soy dough data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	5	26.10774046	5.22154809	44.882	0.0001
ERROR	18	2.09409131	0.11633841		
C TOTAL	23	28.20183177			

ROOT MSE	0.3410842	R-SQUARE	0.9257
DEP MEAN	5.592433	ADJ R-SQ	0.9051
C.V.	6.09903		

NOTE: MODEL IS NOT FULL RANK. LEAST SQUARES SOLUTIONS FOR THE PARAMETERS ARE NOT UNIQUE. SOME STATISTICS WILL BE MISLEADING. A REPORTED DF OF 0 OR B MEANS THAT THE ESTIMATE IS BIASED. THE FOLLOWING PARAMETERS HAVE BEEN SET TO 0, SINCE THE VARIABLES ARE A LINEAR COMBINATION OF OTHER VARIABLES AS SHOWN.

LNPI5 =+0.60811*INTERCEP

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	B	0.91196859	2.71849594	0.335	0.7412
LNPI2	1	-1.01267016	0.18592286	-5.447	0.0001
LNPI3	1	0.18719735	0.18070384	1.036	0.3140
LNPI4	1	0.01075148	0.23770239	0.045	0.9644
LNPI5	0	0	.	.	.
LNPI6	1	-0.11061647	0.34529471	-0.320	0.7524
LNPI7	1	-0.01958339	0.33250461	-0.059	0.9537
LNPI8	0	0	.	.	.

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	7.75500E+12	7.75500E+12	150.681	0.0001
ERROR	23	1.18372E+12	51466202543		
U TOTAL	24	8.93872E+12			

ROOT MSE	226861.6	R-SQUARE	0.8676
DEP MEAN	596944.6	ADJ R-SQ	0.8618
C.V.	38.0038		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	0.82719354	0.06738720	12.275	0.0001

APPENDIX U (Cont'd)

1. Regression of Eqn. 27 for twin-screw extruded SPS data.

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	6	28.33842592	4.72307099	173.484	0.0001
ERROR	21	0.57172090	0.02722480		
C TOTAL	27	28.91014682			

ROOT MSE	0.1649994	R-SQUARE	0.9802
DEP MEAN	6.457089	ADJ R-SQ	0.9746
C.V.	2.555322		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
INTERCEP	1	-0.12425401	1.84586475	-0.067	0.9470
LNPI2	1	-1.15247246	0.05914654	-19.485	0.0001
LNPI3	1	-0.48282691	0.07975095	-6.054	0.0001
LNPI4	1	0.29246896	0.10763972	2.717	0.0129
LNPI5	1	-1.18409473	3.32475756	-0.356	0.7253
LNPI6	1	-0.22026055	0.11409482	-1.931	0.0672
LNPI7	1	-0.06331602	0.15055214	-0.421	0.6783
LNPI8	0	0	.	.	.

2. Regression of predicted vs. observed ΔP_{ent} (intercept = 0).

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	3.43189E+13	3.43189E+13	2523.672	0.0001
ERROR	27	367167053531	13598779760		
U TOTAL	28	3.46860E+13			

ROOT MSE	116613.8	R-SQUARE	0.9894
DEP MEAN	1024732	ADJ R-SQ	0.9890
C.V.	11.37993		

NOTE: NO INTERCEPT TERM IS USED. R-SQUARE IS REDEFINED.

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR H0: PARAMETER=0	PROB > |T|
PENT	1	0.98180232	0.01954374	50.236	0.0001

APPENDIX V INDUSTRIAL APPLICATIONS OF THE DIE PRESSURE DROP MODEL

The following steps outline the procedure for calculating the pressure drop in extruder dies for food industry applications.

DATA COLLECTION

For the following data collection with two or three circular dies with the same cross sections but different lengths will be needed. If a wide range of shear rates is required, it is mormally recommended that two sets of dies are used, one with twice the diameter of the orher. This gives an eight fold change in shear rate as well as additional change in flow rate.

For each material tested, perform the following steps:

1) Accurately calibrate the extruder moisture content and product rate, and use the calibration program given in Appendix D for predicting product rates at the same moisture content of the test material.
2) For the appropriate range of processing conditions (MC,temperature, rpm, etc) collect ΔP vs. Q data for the long/short die combinations. Extreme care should be taken to ensure that extrusion conditions (barrel temperature, work input, etc.) are as similar as possible for each long/short die combination.
3) Record temperature, pressure, product rate, moisture content, and density of material. Record the temperature at the die entrance by inserting a small probe through the die hole to the die cone entry. To determine density, pre-weigh an empty capillary or die of known volume, extrude material into the capillary, and weigh the capillary plus extrudate. Calculate density as follows:

APPENDIX V (Cont'd)

$$\rho = \frac{\text{(Full die weight - empty die weight)}}{\text{volume of die}}$$

4) If the material exhibits elastic properties by swelling at temperatures below 100°C, further data collection will be necessary to estimate the material elastic time constant. For the same product rate and temperature, photograph the extrudate swell for three different L/Ds of equal diameter dies.

5) If the data of step 3 does not have significant variation in temperature this step can be omitted.
Use a rheometer that maintains constant temperature to determine viscosity as a function of temperature for temperature-time histories and moisture contents similar to those for the extrusion process. For doughs of low viscosity a rotary viscometer is the simplest kind to use. For most doughs of moderate to high viscosities a tube or capillary rheometer will be required.

DATA ANALYSIS

6) Adjust data to the average extrusion die temperature. At low medium and high shear rates, use step 5 to collect data required to model η as a function of temperature according to

$$\eta_{\gamma\text{-constant}} = A\ e^{(\Delta Ev/RT)}$$

7) Adjust extrudate pressure data to an average temperature as follows:

APPENDIX V (Cont'd)

$$\Delta P_{adj} = \Delta P_{obs} e^{\frac{\Delta Ev}{R}[T_{Ave.}^{-1} - T_{meas.}^{-1}]}$$

where $\Delta Ev/R$ is the slope of the line in step 6 and $T_{Ave.}$ is the mean of all temperatures recorded in step 3.

8) Extrapolate extruder ΔP data for each shear rate as shown in Figure 10 and obtain ΔP_{ent} for each long/short die combination.

9) Convert extruder ΔP vs. Q data to shear stress vs. shear rate data. Plot τ_w vs. Γ on log-log paper. Use linear regression to obtain the slope and intercept of a line through this data where n is the slope of this line and m is computed as follows:

$$m = \text{intercept}/((3n+1)/(4n))^n$$

Note, the above relationship assumes a Power-law fluid approximation.

10) Elastic time constant calculation

For nonelastic materials, this step can be skipped. For elastic materials, a method is proposed for determining an elastic time constant.

A) Compute a swell ratio, β, = extrudate diameter/die diameter.

B) Plot the swell ratio, β, vs. die residence time (See Figure 21) and compute λ as (Williams, 1977):

APPENDIX V (Cont'd)

$$\lambda = \frac{\ln\left(\frac{\beta - \beta_\infty}{\beta_o - \beta_\infty}\right)}{-t} \quad (8)$$

where t is the die residence time.

11) Prediction of entrance pressure drop.

A) Compute π_1 and π_2 for all data as follows:

$$\pi_1 = \frac{16\ n_d^2 r_h^4\ \Delta P_{ent}}{\rho\ Q^2} \quad (11)$$

$$\pi_2 = \frac{\rho\ Q}{\pi n_d r_h \bar{\eta}} \quad (12)$$

where

$$\bar{\eta}\ (\gamma_{wall}) = m \left(\frac{Q}{2\pi n_d r_h^3}\right)^{n-1} \left(\frac{3n+1}{4n}\right)^{n-1}$$

If the material is elastic compute π_8 as follows:

$$\pi_8 = 1 + \frac{\lambda\ Q}{16\pi\ n_d r_h^3} \quad (13)$$

If data of more than one material was collected, compute π_5 as follows:

$$\pi_5 = (3n+1)/(4n) \quad (14)$$

APPENDIX V (Cont'd)

B) Regress $\ln\pi_1 = \ln a + b_2\ln\pi_2 + b_5\ln\pi_5 + b_8\ln\pi_8$ using a rendition of the SAS program given in appendix S.

C) Model ΔP_{ent} as follows:

$$\Delta P_{ent} = \frac{\rho Q^2}{16 n_d^2 r_h^4} [a(\pi_2)^{b_2} (\pi_5)^{b_5} (\pi_8)^{b_8}] \qquad (15)$$

12) For predicting ΔP_{dhole} of circular or noncircular holes use the following approximation:

$$\Delta P_{dhole} = \frac{L\, m}{(8\pi)^n r_h (3n+1)} \left(\frac{3n+1}{n} \right)^n Q^n \frac{1}{f_c} \qquad (16)$$

where f_c is obtained from Figure 3.

13) For prediction total die pressure drop for circular or non circular dies use the following approximation:

$$\Delta P_T = \Delta P_{ent} + \Delta P_{dhole} \qquad (17)$$

LIST OF REFERENCES

Agricultural Engineers Yearbook of Standards.1986. ASAE. St. Joseph, MI.

Altomare, R.E. and Ghossi, P. 1985. An analysis of residence time distribution patterns in a twin screw cooking extruder. Biotech. Prog. 2(3):157-161.

Astarita, G. 1974. Dimensional analysis of flow of viscoelastic fluids. Chem. Engr. Sci. 29(5): 1273-1278.

Bagley, E.B. 1957. End corrections in the capillary flow of polyethylene. J. Appl. Phys. 28(5):624.

Ballenger, T.F., Chen, I.J., Crowder, J.W.,Hagler, G.E., Bogue, D.C. and White, J.L. 1971. Polymer melt flow instabilities in extrusion: investigation of the mechanism and material and geometric variables. Trans Soc Rheol 15(2): 195-215.

Bigg, D. and Middle, S. 1974. Mixing in a Screw extruder. A model for residence time distrubution and strain. Ind. Eng. Chem. Fundam. 13(1): 66-71.

Boger, D.V. 1982. Circular entry flows of inelastic and viscoelastic fluids. In: Mujumdar, A.S. and Mashelkar. 1982. Advances in Transport Processes. John Wiley & Sons, Newy York, NY. 2: 43-104.

Bruin, S., Van Zuilichem, D.J. and Stolp, W. 1978. A review of fundamental and engineering aspects of extrusion of biopolymers in a single screw extruder. J. Food Proc. Engr. 2(1): 1-37.

Carreau,P.J., Choplin,L. and Clermont, J-R. (1985). Exit pressure effects in capillary die data. Polym. Eng. and Sci. 25(11):669-676.

Collins, M. and Schowalter,W.R. 1963. Behavior of non-Newtonian Fluids in the entry region of a pipe. AICHE J. 9(6):804-809.

Crater, D.H. and Cuculo, J.A. 1984. Flow characteristics of polyethylene terephthalate deduced from pressure drop measurements. J. Polymer Sci. Polym. Phys. Ed. 22(1): 1-19.

Darby, R. 1976. Viscoelastic Fluids: An Introduction to their Properties and Behavior. Marcel Dekker Inc., New York, NY.

Han, C.D. 1973. Influence of the die entry angle on the entrance pressure drop, recoverable elastic energy, and onset of flow instability in polymer melt flow. J. Appl Poly Sci. 17(5): 1403-1413.

Han, C.D., 1976. Rheology in Polymer Processing. Academic Press, NY, NY.

Harmann, D.V. and Harper, J.M. 1974. Modeling a forming foods extruder. J. Food Sci 39(6): 1099-1104.

Harper, J.M. 1981. Extrusion of Foods, Vol. 1 CRC Press. Boca Raton, FL.

Harper, J.M. 1986. Extrusion texturization of foods. Food Tech. 40(3): 70-76.

Huang, D. and White,J.L. 1980. Experimental and theoretical investigation of extrudate of polymer melts from small (length)/(cross-section) ratio slit and capillary dies. Polym. Engr. and Sci. 20(3): 182-189.

Jao, Y.C. and Chen, A.H. 1978. Engineering analysis of soy dough rheology in extrusion. J. Food Proc. Engr. 2(1): 97-112.

Jasberg, B.K., Mustakas, G.C. and Bagley, E.B. 1982. Effect of extruder retention time on capillary flow of soy dough. J. Food Proc. Engr. 5(1): 43-56.

Keunings, R. and Crochet, M.J. 1984. Numerical simulation of the flow of a viscoelastic fluid through an abrupt contraction. J. non-Newtonian Fluid Mech. 14(1): 279-299.

Kim-E, M.E., Brown, R.A. and Armstrong,R.C. 1983. The roles of inertia and shear thinning in flow of an inelastic liquid through an axisymmetric sudden contraction. J. of non-Newtonian Fluid Mech. 13(3): 341-363.

Knudsen,J.G. and Katz,D.L. 1958. Fluid Dynamics and Heat Transfer. McGraw-Hill, New York NY.

Lahti,G.P. 1963. Calculation of pressure drop and outputs. SPE J. July pp591-592.

La Nieve, H.L. and Bogue, D.C. 1968. Correlation of capillary entrance pressure drops with normal stress data. J. Appl. Polym. Sci. 12(2):353-372.

Lenk,R.S., and Fenkel,R.A. 1981. Flow in elliptical channels. J. Appl. Polym. Sci. 26(9):3171-3173.

Mackey, K.L., Morgan, R.G., and Steffe, J.F. 1986. A generalized viscosity model for extrusion of starch doughs. Submitted for publication in J. of Food Process Engineering

McCabe, W.L. and Smith, J.C.1976. Unit operations of Chemical Engineering. Mc Graw-Hill, Inc.

Mennig, G. 1976. Visual studies of the wall slipping behavior of high polymer melts. Rheo. Acta 15(3/4):199-205.

Michaeli, W. 1984. Extrusion Die-Design and Engineering Computations. Hanser Publishers, Munich, distributed by Macmillan Publishing Co., Inc., New York, NY.

Mitsoulis, E., Vlachopoulos, J. and Mirza, F.A. 1985. A study of the effect of normal stresses and elongational viscosity on entry growth and extrudate swell. Polym. Engr. and Sci. 25(11): 677-689.

Morgan,R.G., Suter,D.A. and Sweat,V.E. 1978. Design and modeling of a capillary food extruder. J. Food Proc. Engr. v2:65-81.

Morgan, R.G. 1979. Modeling effects of temperature-time history, temperature, shear rate and moisture on viscosity of defatted soy flour dough. Ph.D. Dissertation. Texas A & M University.

Morgan,R.G., Steffe, J.F. and Ofoli,R.Y. 1987. A generalized rheological model for extrusion modeling of protein doughs. To be submitted to J of Food Process Engr.

Murphy, G. 1950. Similitude in Engineering. The Ronald Press Co., New York, NY.

Pena, J.J., Guzman, G.M., and Santamaria, A. 1981. Determination of capillary entramce pressure losses and first normal stress difference in polystyrene and high impact polystyrene melts. Polym. Engr. and Sci. 21(5): 307-311.

Shenoy, A.V. and Saini, D.R. 1985. Prediction of pressure losses through typical die shapes based on a simple, novel approach. Polym.-Plast. Tech. 23(2): 169-183.

Tanner, R.I., Nickell, R.E. and Bilger, R.W. 1975. Finite element methods for the solution of some incompressible non-Newtonian fluid mechanics problems with free surfaces. Computer Methods in Appl. Mech. and Engr. 6(1): 155-174.

van Zuilichem,D.J.,Janssen,L.P.B.M., and Stolp,W. 1983. Extrusion of reacting biopolymers. in: Progress in Food Engineering Solid Extraction Isolation and Purification Texturization. ed. by C. Cantareller and C. Peri. Forster Publ. Ltd. Switzerland.

Whorlow, R.W. 1980. Rheological Techniques. Halsted Press, New York, NY.

White, J.L. and Roman, J.F. 1976. Extrudate swell during the melt spinning of fibers- influence of rheological properties and take-up force. J. of Appl. Polym. Sci. 20(4): 1005-1023.

Williams, D.J. 1971. Polymer Science and Engineering. Prentice-Hall Englewood Cliff, N.J. p365.

Worth, R.A., Parnaby, J. and Helmy, H.A.A. 1977. Wall slip and its implications in the design of single screw melt fed extruders. Polym. Engr. and Sci. 17(4):257-265.

BIOGRAPHICAL SUMMARY OF MURRAY D. HOWKINS **October 1987**

BIRTHDATE: August 26, 1963
CITIZENSHIP: U.S.
MARITAL STATUS: Single
HOME ADDRESS: 3000 Trilogy, Milford, MI 48042 — wk phone #(201) 797-6800, hm phone #(313) 685-1542

CURRENT POSITION: Engineering Consultant to Nabisco Brands

PROFESSIONAL TRAINING: Passed Engineer-in-Training Exam

EDUCATION:

Dec. '87 M.S. Candidate in Agricultural/Food engineering, Michigan State University. Thesis topic: Pressure drop vs. flow rate modeling for extrusion dies.

June '85 B.S. Agricultural Engineering, Michigan State University. Concentration of study: 1983-85 Agri. Engr., Michigan State University; 1981-83 Mech. Engr., University of Michigan.

EXPERIENCE:

1987-present. Engineering Consultant to Nabisco Brands, Inc.

1985-1987. Res. Assis., Agri. Engr., Michigan State University

Project leader of installation of new Baker Perkins 50mm Twin Screw Extruder, including complete equipment installation, developing training materials as well as training/certifying operators.

Project leader of research on food extruder die flow analysis methods: organizing/operating extrusion tests.

1984/spring. Agricultural Aide, Colombia, South America
Provided farm training for Colombian students.

1979-1986/summers. Equipment operator. Dyrland Farms, Inc, Big Sandy Montana, and Drever's Dairy, Balzac Alberta. Operated and maintained heavy farm equipment, assisted in dairy operations.

FOREIGN LANGUAGES:

Spanish: Four years study in high school, three months practice in Colombia. Able to participate in general communications. Reading and writing at junior high school level.

Mandarin Chinese: Currently studying under private tutor.

ACADEMIC HONORS:

Michigan State Dean's Honor list, University of Michigan Dean's Honor list, National Honor society, Phi Beta Kappa

SOCIETY MEMBERSHIPS:

American Society of Agricultural Engineers:
Alpha Epsilon (Honor society of Agricultural Engineering)

PUBLICATIONS:

Howkins, M.D., Morgan, R.G., Steffe,J.F. 1986. Extrusion die swell phenomena of starch based doughs. ASAE paper No. 86-6523. ASAE, St. Joseph, MI. Presented at the ASAE 1986 winter mtg, Chicago IL.

Howkins, M.D., Morgan, R.G. 1986. Similitude approach to food extrusion die flow problems. ASAE paper No. 86-6001. ASAE, St. Joseph, MI. Presented at the ASAE 1986 summer mtg, Cal-Poly State Univ. San Luis Abispo.

REFERENCES:

Ronnie G. Morgan, Ph.D., PE.
Mgr Process Research and Development
Grocery Products and Venture Technology
Kraft, Inc.
801 Waukegan Rd Glenview, IL 60025
(312) 998-7440

Rudy Leschke, Mgr. extrusion engineering
Nabisco Brands, R&D Ctr.
2111 Rt. 208
Fairlawn NJ, 07410
(201) 797-6800

Howard A. Dyrland
Dyrland Farms, Inc.
Big Sandy, Montana 59520
(406) 378-2267