# SINGLE SCREW EXTRUDER PERFORMANCE CHARACTERISTICS DURING PROCESSING OF CORN PROTEIN BLENDS

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*Abstract*—**During the last decade, the global biofuels industry has experienced exponential growth. By-products such as distillers dried grains with solubles (DDGS) have grown in parallel. DDGS is primarily an animal feed, but it has also been shown to be suitable as a biopolymer. In this study, the extrusion processing behaviour of DDGS was evaluated. Prior to processing, water was added to DDGS at a level of 3 kg DDGS to 1.5 kg water (water at 50 parts per hundred (pph)). Additionally, a DDGS/water blend with 50 pph $CaCO_3$ was used as a tracer to determine residence time during processing. The blends were processed in a single screw autogenous extruder, which relied solely upon friction for dissipative heating. Two die plates were used: one consisted of 6 orifices equally spaced, 2 mm diameter each, with a total opening area of 18.85 $mm^2$; the other consisted of multiple orifices (960 in total) arranged concentrically around the plate, with a diameter of 2.30 mm each, for a total opening area of 3988.45 $mm^2$. Processing began with DDGS blends without tracer; after reaching steady state, the tracer blend was introduced. Samples were collected every 5 sec during processing to determine extrudate changes over time. Extruder power consumption, mass flow rate, and temperature profile were determined during processing. Extrudates were analysed for Hunter colour (L-a-b) changes over time. Extrusion processing characteristics were highly influenced by the die opening area. Die exit temperatures ranged from room temperature ($25^o$C) to more than $100^o$C, purely due to increased friction for the smaller die opening. Future work should characterize the mechanical properties of these extrudates to assess their suitability as either bioplastic feedstocks or pelletized animal feeds.**

*Keywords-corn ethanol, coproducts, extrusion, processing.*

## I. INTRODUCTION

Petroleum-based polymers have become ubiquitous due to their excellent properties and durability. Unfortunately, they also create an enormous environmental burden. Motivations behind research in reducing dependence on polymers from petrochemical sources are similar to those in energy research: a decreasing fossil fuel supply with a corresponding price increase and a growing awareness of environmental sustainability [3].

There are two primary ways to address the energy challenge: reduce energy consumption and/or develop alternative methods of energy production. Biofuels are renewable sources of energy and are a promising alternative. One of the most frequently used materials for energy production is corn [4]. Ethanol production from corn can be accomplished very efficiently and at a relatively low cost. The main approach to producing corn-based ethanol is known as dry grinding, which subjects the entire corn kernel to processing, although starch is the only material that is actually converted into fuel [1]. After milling, the resulting corn flour is combined with water, enzymes, and yeast, and is then cooked and fermented. Ethanol is extracted using distillation and centrifugation to remove residual non-fermentable corn kernel components, water, and carbon dioxide. The non-fermentable materials are usually combined, dried and sold as 'distillers dried grains with solubles', or DDGS, for use as animal feed. DDGS also has potential as a feedstock for use in bio-based plastics [4].

The potential use of agro-polymers in the plastics industry has long been recognized. Agro-polymers can be extracted from either plants or animals, using polysaccharides or proteins. Some of these polymers can be processed directly into thermoplastic materials; however, most require chemical modification. A further benefit is that these polymers are often by-products of other agricultural activities. Common characteristics of agro-polymers are their hydrophilicity, fast degradation rate, and often unsatisfactory mechanical properties, particularly in wet environments [6]. These polymers can be considered an innovative and sustainable

approach to reduce reliance on petrochemical polymers [2]. The main technological challenge is to successfully modify the properties of these materials to account for deficiencies such as brittleness, water sensitivity, and low strength. Additionally, the perceived competition between bioplastics and food production can be problematic as the industry develops. As a result, attention is shifting to second generation bioplastics, which are manufactured from non-potential food sources, especially by-products.

However, one of the key challenges for bioplastics is to successfully use these bio-based materials in common plastic processing operations, such as extrusion and injection moulding. The objectives of this research were to examine the extrusion processing behaviour of DDGS, to quantify extruder power consumption, mass flow rate, temperature profile, and residence time during processing.

## II. EXPERIMENTALS

### A. Materials

DDGS was procured from VeraSun Energies (Aurora, SD, USA), after having the lipids removed by solvent extraction [5]. Composition of this deoiled protein meal is provided in Table I.

TABLE I    COMPOSITION OF THE RAW DEOILED DDGS USED IN THE STUDY.

| Component | %, dry basis |
|---|---|
| Dry Matter | 98.0 |
| Crude Protein | 34.0 |
| Crude Lipid | 2.7 |
| Carbohydrate | 58.5 |
| Neutral detergent fiber | 50.1 |
| Starch | 5 |
| Ash | 4.8 |

### B. Ingredient Preparation

Prior to processing, water was added to the DDGS at a level of 3 kg DDGS to 1.5 kg water (water at 50 parts per hundred (pph)). Additionally, a DDGS/water blend with 50 pph $CaCO_3$ was prepared as a tracer to determine extruder residence time during processing. The blends were thoroughly mixed for 30 min in a rotating mixer, sealed in plastic containers, then left over night to equilibrate.

### C. Extrusion Processing & Extrudate Analysis

After preparation, the DDGS blends were extruded in a single screw autogenous (i.e., heat was not added externally; rather all heat was generated due to friction alone) extruder (Rietz, Extructor, Bepex International LLC, Minneapolis, MN (Figure 1)). The extruder had a split barrel with three chambers (Figure 2); the front (i.e., die) section was fitted with two thermocouples, with one placed at the entry to the section (which recorded $T_2$) and the second placed near the die exit

(which recorded $T_1$). Two die plates were used (Figure 3): one consisted of 6 orifices equally spaced, 2 mm diameter each, with a total opening area of 18.85 $mm^2$; the other consisted of multiple orifices (960 total) arranged concentrically around the plate, with a diameter of 2.30 mm each, for a total opening area of 3988.45 $mm^2$.

Processing began using the DDGS blends without tracer; after reaching steady state operation, the tracer blend was introduced. The thermocouples recorded temperature profile over time. Samples were collected every 5 sec during processing to determine mass flow rate through the extruder and then used to determine extrudate changes over time. A power meter (HIOKI 3196, HIOKI E.E. Corporation, Nagano, Japan) was used to continuously record extruder power consumption.

Extrusions were carried out in duplicate for each blend combination (i.e., n = 2 for each die opening). The input feed rate was set ensure steady state operation of the extruder, and was approximately 132 kg $h^{-1}$ (SD =11.3). After processing, the extrudates were cooled to room temperature, dried at 40°C for 24 h, then stored in sealed polyethylene bags at room temperature until further analysis. Extrudates were subsequently analysed for Hunter colour (L-a-b) changes over time.

## III. RESULTS AND DISCUSSIONS

Extrusion resulted in semi-continuous, pelleted extrudates. The extrudates produced with the smaller die opening area seemed to be somewhat darker than those produced with the larger die opening, which was likely due to proteins denaturing due to higher processing temperatures and times for the smaller die.

### A. Mass Flowrate

For each die used, mass flowrate increased over time as the machine moved toward steady-state processing. It was readily apparent (Figure 4) that the die plate with a greater amount of opening area had much greater flowrate, and quickly achieved steady-state processing. The smaller die plate constricted flow, however, and steady state was not quite achieved even at the end of the experimental runs. The large die opening exhibited curvilinear behavior as it approached steady state, while the smaller die opening increased in a linear fashion.

### B. Power Consumption

Power consumption curves for each blend generally followed similar trends (Figure 5), with distinct changes after the first extruder chamber became completely filled, when the second chamber became completely filled, and when the third was filled, at which point quasi-steady state was achieved for the machine. All blends continued to show power consumption increases over time, though, which was due to shear forces generating frictional heat, cooking, and then further modifying the protein structures. As shown in Figure 6, power required for the greater die opening area was much lower than for the small die opening area.
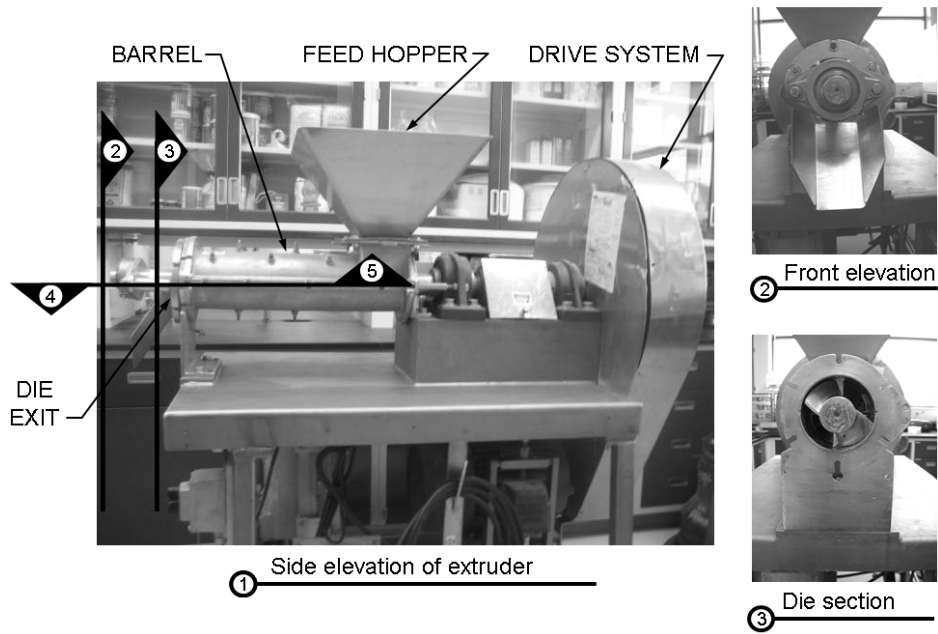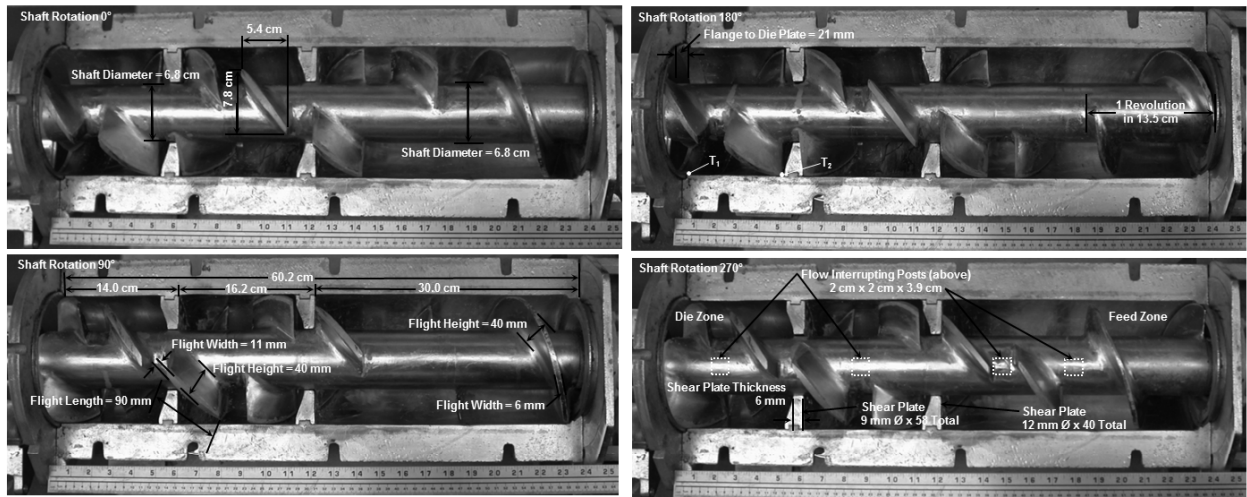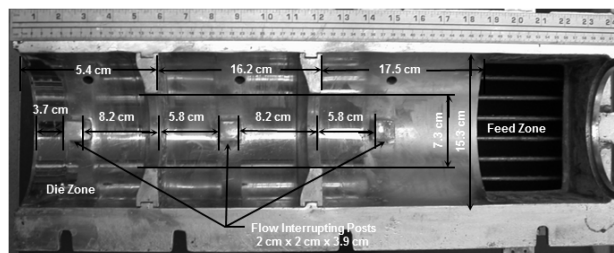
FIGURE 1 SINGLE SCREW AUTOGENOUS (I.E., SELF-HEATING) EXTRUDER USED IN THIS STUDY.



FIGURE 2 EXTRUDER INTERNAL BARREL CONFIGURATION AND DIMENSIONS. SCALE BAR INDICATES BOTH CM AND INCHES.
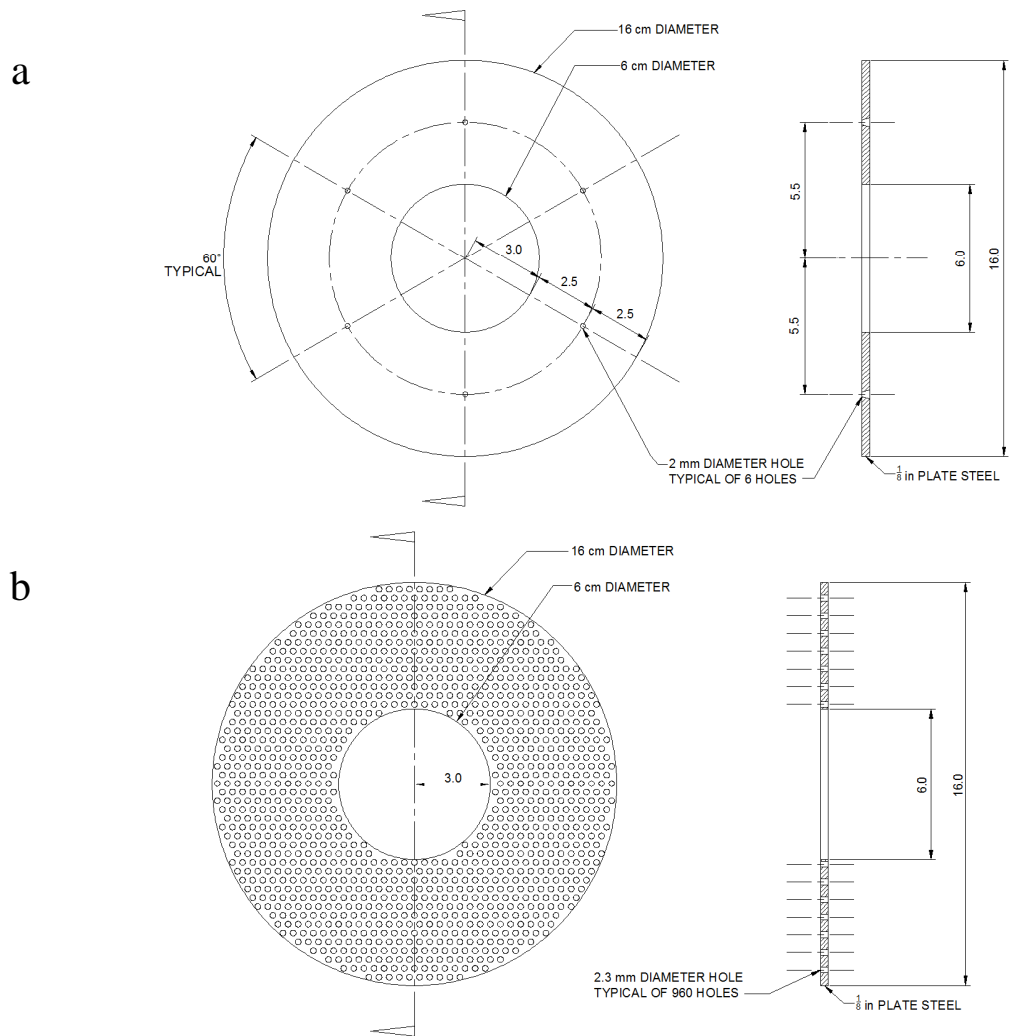
FIGURE 3    DIE PLATES USED IN THIS STUDY.  (A) DIE PLATE A, 6 HOLES, 2 MM DIAMETER EACH, 18.85 MM$^2$ TOTAL OPEN AREA.  (B) DIE PLATE B, 960 HOLES, 2.3 MM EACH, 3988.45 MM$^2$ TOTAL OPEN AREA.  ALL DIMENSIONS ARE CM UNLESS NOTED OTHERWISE.
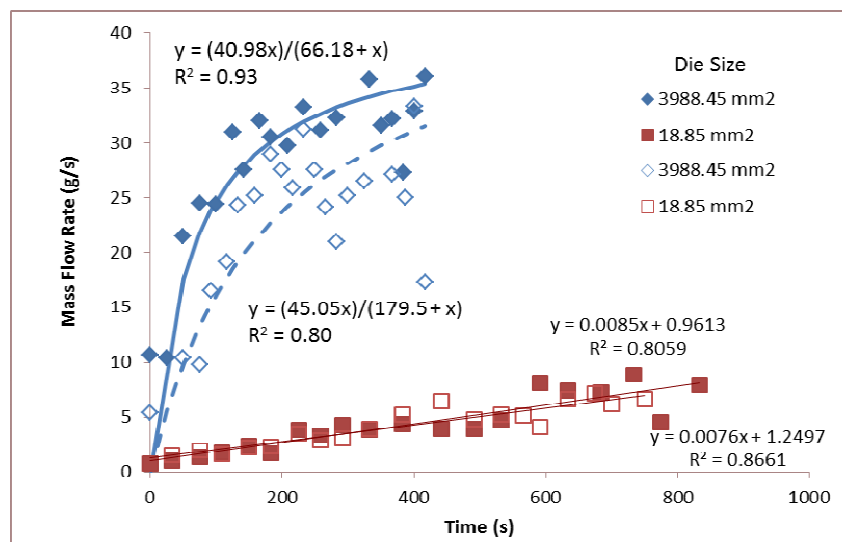


FIGURE 4    MASS FLOWRATE THROUGH THE EXTRUDER OVER TIME.

This was due to the greater flow restriction with the smaller die, which led to greater retention time in the extruder and thus much more frictional heat generation. The greater die opening area allowed the extruder to rapidly reach steady state operation, as shown by relatively constant power consumption over time (~ 250 W). The smaller die opening, however, didn't quite reach steady state during the trials, but rather continued to require great amounts of power over time (almost 900 W by the end of the extrusion), although the rate of increase was not nearly as great as when the chambers were filling.
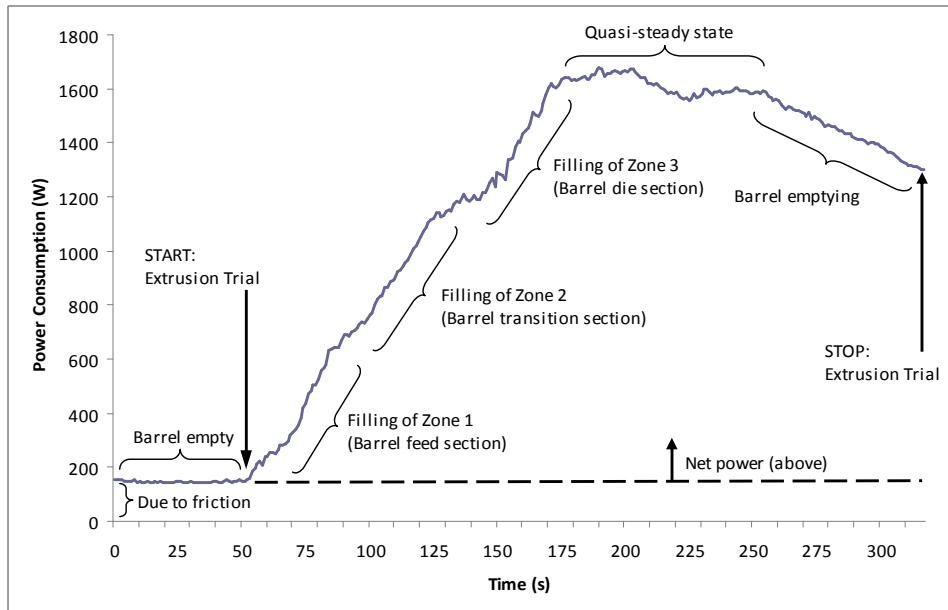


FIGURE 5    TYPICAL EXTRUDER POWER CONSUMPTION CURVE. MEAN POWER CONSUMPTION WAS DETERMINED BY AVERAGING NET CONSUMPTION (I.E., EXCLUDING FRICTION) FROM BEGINNING TO END OF THE TRIAL.
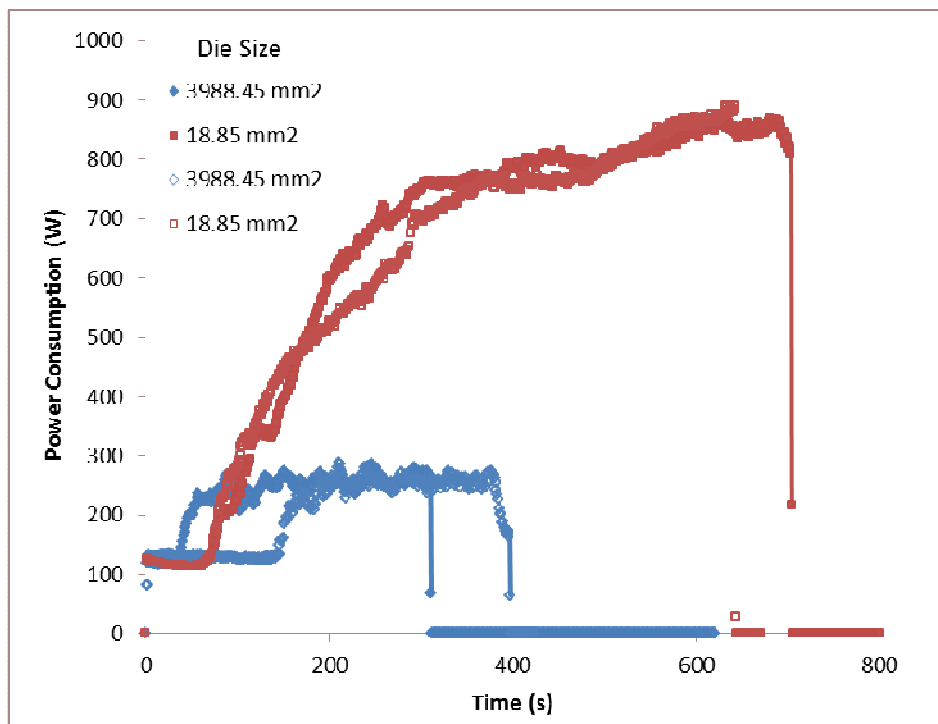


FIGURE 6    EXTRUDER POWER CONSUMPTION OVER TIME DURING PROCESSING. THE SMALL DIE OPENING RESTRICTED FLOW, AND RESULTED IN GREATER POWER CONSUMPTION.

Integrating these data to determine the area under each power curve provided total energy consumed. Dividing instantaneous net energy consumption (accounting for friction) by instantaneous mass flowrate provided the specific mechanical energy consumption (SME). The greater the SME, the greater the power input per unit of product – this power was converted into frictional heating between the extruder screw and the DDGS. Using the die with the large opening area required very low SME, because flow was not restricted (Figure 7). Using the die with the small opening area, however, resulted in very high SME required. SME increased rapidly until about 150 s to 200 s, which corresponded to the first two chambers of the extruder filling. After this time the third chamber was filling, and the trajectory of the SME was not as rapid (the SME changed abruptly when the third chamber began filling). After the third chamber was completely filled (at approximately 300 s), the SME steadily declined. This likely occurred due to the pseudoplastic behaviour of the DDGS, as well as structural breakdown of the proteins as the frictional shear and thus temperature increased.
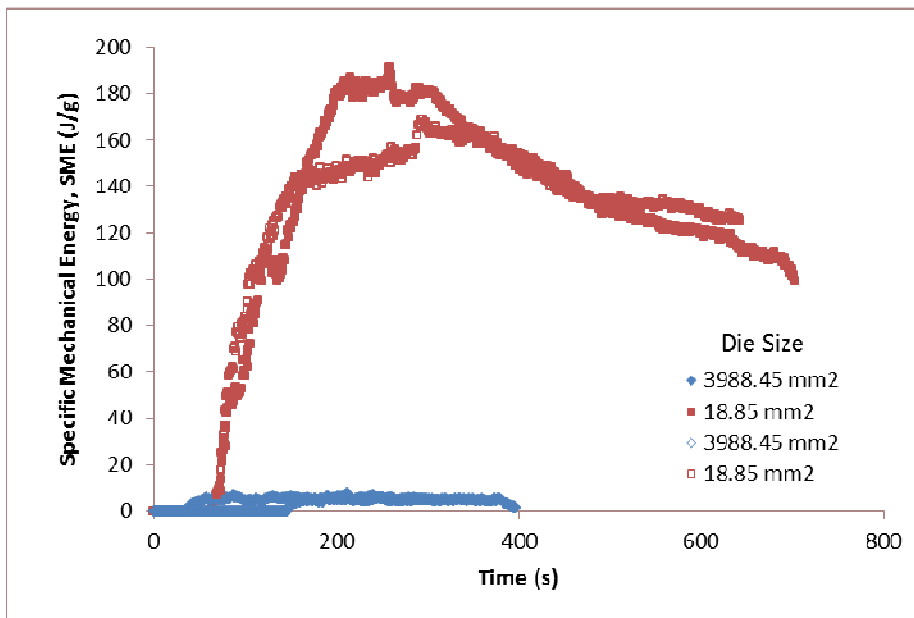


FIGURE 7  EXTRUDER SME OVER TIME DURING PROCESSING. THE SMALL DIE OPENING RESTRICTED FLOW AND RESULTED IN GREATER SME. AFTER THE THIRD CHAMBER FILLED THE SME DECREASED AS STRUCTURAL BREAKDOWN OCCURRED DUE TO INCREASED SHEAR AND FRICTIONAL HEATING.

*C.  Temperature Profile*

Temperature rise in the extruder barrel (Figure 8), for both zone 2 (central extruder chamber) and zone 1 (chamber at which the material exited the die), increased over time. Zone 1 always had a higher temperature response because that was the chamber where the majority of frictional energy was imparted to the dough. Zone 2 was primarily a zone for conveying/material transfer. A greater die restriction (i.e., smaller die opening area) always led to increased temperature in this region (Figure 9). After zones 1 and 2 were filled (~ 150 s to 200 s), the die one began to frictionally heat, and the die temperature rose quickly (~ 0.11°C/s). The larger die opening area did not result in high frictional heating, because flow was not restricted and mass flowrate was higher (i.e., residence time was lower), so die temperature did not rise much above room temperature.

*D.  Residence Time*

Extrudate Hunter colour parameters were determined and used to estimate DDGS residence time distribution within the extruder during processing. Brightness/darkness (Figure 10) and yellowness/blueness (Figure 11) of the extrudates increased slightly over time, and unfortunately these results were not conducive to determining extruder residence time.

Extrudate redness/greenness, however, appeared to change over time (Figure 12), and thus estimates of residence time could be made. The larger die opening area had an approximate residence time of 200 s (as evidenced by the relatively constant Hunter a value of approximately 6.5 which occurred after this time point), but that for the small die opening was greater than 900 s (complete equilibrium was never achieved during processing). These results are reflective of the mass flowrate data: the larger the die opening area, the greater the flowrate, and the lower the residence time. Additionally, because the die was not as restricted, frictional heating was lower.
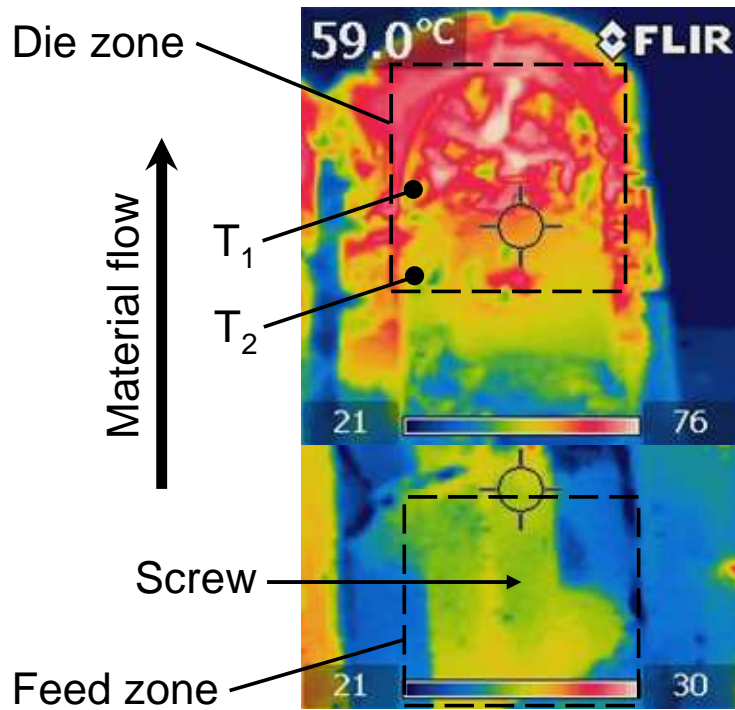
FIGURE 8   THERMAL IMAGING OF THE EXTRUDER INTERIOR (CUT SECTION 4, FIGURE 1) DURING PROCESSING ILLUSTRATES THAT ALMOST ALL OF THE TEMPERATURE RISE DURING PROCESSING OCCURS IN THE DIE SECTION, AND IS DUE TO FRICTION BETWEEN INGREDIENT PARTICLES AND THE EXTRUDER SCREW, AS WELL AS THE BACK PRESSURE DUE TO THE RESTRICTION IMPOSED BY THE DIE.  COLOUR SCALE BARS ARE INDICATIONS OF TEMPERATURE (ºC).  (NOTE THAT TWO INDIVIDUAL IMAGES WERE FUSED, THUS TWO SEPARATE SCALE BARS ARE SHOWN.)
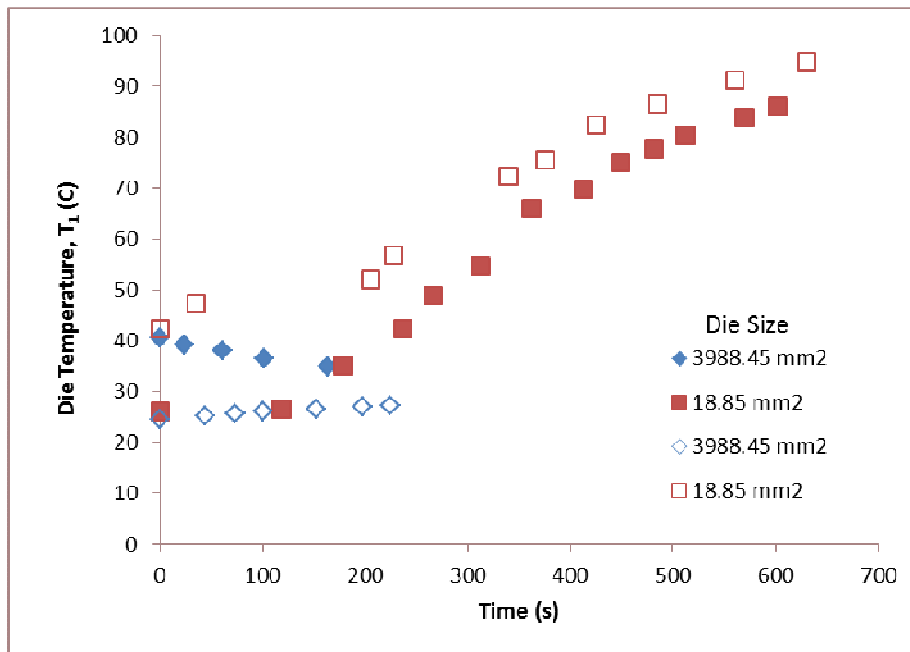


FIGURE 9   DIE TEMPERATURE ($T_1$) OVER TIME DURING PROCESSING.  THE SMALL DIE OPENING RESTRICTED FLOW WHICH RESULTED IN GREATER FRICTIONAL HEATING; THE LARGER DIE OPENING RESULTED IN LOWER FRICTIONAL HEATING BECAUSE FLOW WAS NOT RESTRICTED.
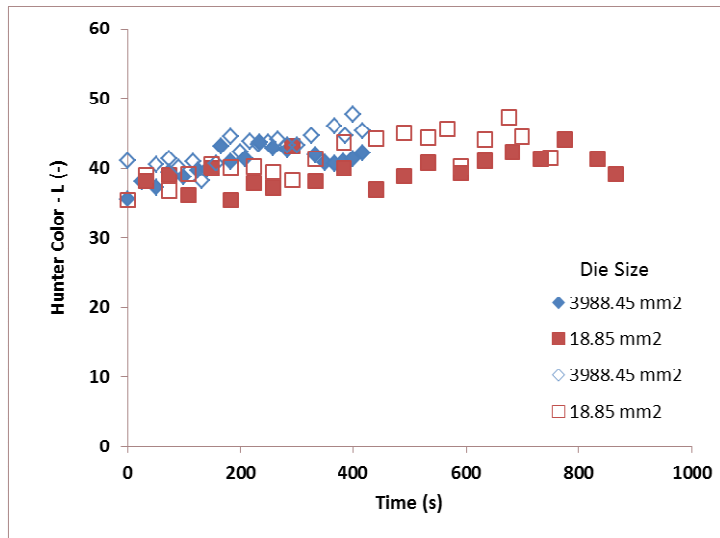
FIGURE 10    EXTRUDATE HUNTER L (LIGHTNESS/DARKNESS) CHANGES OVER TIME DURING PROCESSING.
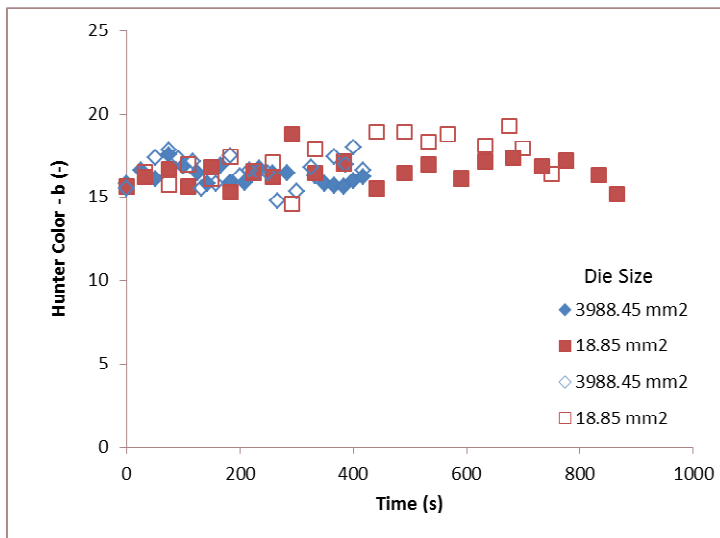


FIGURE 11    EXTRUDATE HUNTER B (YELLOWNESS/BLUENESS) CHANGES OVER TIME DURING PROCESSING.
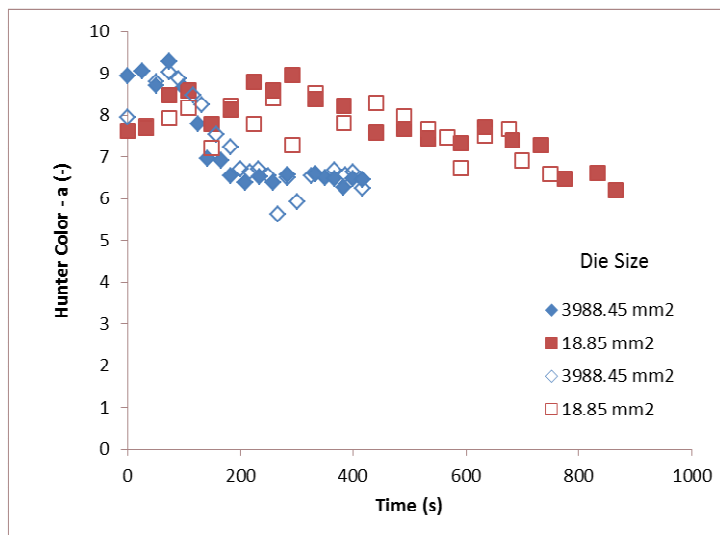


FIGURE 12    EXTRUDATE HUNTER A (REDNESS/GREENNESS) CHANGES OVER TIME DURING PROCESSING.

## CONCLUSIONS

It was thought that the non-protein (i.e., fibre) fraction in the DDGS would reduce the ability of the corn proteins to consolidate. But, semi-continuous extrudates formed, suggesting that there was enough consolidation required for bioplastics or animal feed formation. It was readily apparent that extruder die opening plays a key role in processing conditions. Smaller die opening area resulted in lower mass flow rate, greater power consumption, and greater temperature increase, as input power to the extruder shaft was converted to dissipative energy in the dough. Although not part of this investigation, changing screw speed and moisture content will interactively influence power consumption, die temperature increase, and residence time in the extruder. Investigating these differences is a necessary topic for further research.

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