HIGH MOISTURE EXTRUSION OF OATMEAL

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ABSTRACT

High Moisture Extrusion of Oatmeal

Brandon Fletcher Coleman

Oats are considered to be a highly nutritious breakfast food available to consumers. Heightened consumer interest in functional food products and advances in human nutrition have led to increased levels of interest in the development of new oat based products (Webster and Wood 2011). Developments in technology have led to manufacturing of instant oatmeal, making the product more convenient to consumers. Low moisture extrusion processing is one of the most widely used methods to produce ready to eat breakfast cereals; however, there has been little research carried out to determine if high moisture extrusion methods would be viable. This study evaluated the economic and technical feasibility to utilize high moisture extrusion processing to produce ready to eat oatmeal. A process economics evaluation included measuring the capital requirements to implement the system, process costing to estimate the weighted average unit cost, and net present value of high moisture extrusion production. The capital expense was significantly high. However, the unit cost is comparable to similar products in the market. The net present value of implementing the technology revealed a significant profit over the course of 20 years. Six different technical experiments were performed using a twin screw extruder, each experiment testing for the effect of different extrusion variables on finished product texture. Reference texture data was measured using a control product currently made in the industry using an alternative batch process. The processing parameters which seemed to have the biggest influence on product quality were high rates of water injection, low feed rate, high reaction zone temperature, reduction of particle size, and the use of functional ingredients in the formula. Technical hurdles such as low dwell times, steam plugging, and inconsistent feeding prevented complete starch gelatinization and the steady state of extrusion. Overall, the high moisture methodology did not yield product quality that was consistent and cannot be recommended for use.

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CHAPTER 1

Introduction

1.1 Background Information and Problem Statement

Oats make up less than 2 % of total grain production in the U.S. and are the sixth most grown cereal grain after corn, wheat, barley, sorghum, and millet (Webster and Wood 2011). The increasing awareness of the nutritive and functional properties of oats enhances the possibility for sustainable growth in the marketplace. In many countries, oats are used as a mixed feed source for livestock; however, there are many oat- based products for human consumption as well (Chang and others 1985). Oats are considered to be one of the most nutritious breakfast foods available to consumers. This nutritionally dense cereal is composed of one third more protein, four times more fat as well as less starch than wheat. Heightened consumer interest in functional food products and advances in human nutrition have led to increased levels of interest in the development of new oat based products (Webster and Wood 2011).

Developments in technology have led to manufacturing of instant oatmeal, making the product more convenient to consumers. Low moisture extrusion processing is one of the most widely used methods to produce ready to eat breakfast cereals; however, there has been little research performed to determine if high moisture extrusion methods would be viable. In order to determine high moisture extrusion feasibility, it is necessary to understand how oatmeal ingredients are affected by varying extrusion processing variables. The quality of oatmeal is driven by the degree of starch gelatinization. Achieving gelatinization of starch is a function of heat, water addition, and mixing. Therefore, it is important to determine the efficacy of this technology to produce high quality starch based products.

1.2 Importance of the Project

Currently, the food industry is experiencing negative quality attributes using the batch method to produce oatmeal. Kettle cooking is a commonly used methodology to produce ready to eat oatmeal. Quality attributes such as texture, flavor, and appearance are inconsistent from batch to batch (Wawona Frozen Foods 2014). There is interest in finding a new way of producing oatmeal that would lead to fewer consumer complaints related to product quality. The industry provided a batch made product which served as a control (Figure 1.1). Through performing this research, we can determine if it is possible to achieve desired quality using high moisture extrusion technology. Quality improvements could include consistent texture, moisture dispersion and absorption, as well as optimal starch gelatinization. In performing the economic analysis, we may be able to improve the efficiency of the oatmeal making process as well. Some potential economic performance measures that could be improved with high moisture extrusion are production labor efficiency, throughput capacity, and total cost per unit.

Figure 1.1 Kettle Batch Control Product

1.3 General Hypothesis

This study will test the overall hypothesis that it would be economically and technically feasible to utilize high moisture extrusion processing to produce ready to eat oatmeal. Efficacy will be measured technically through evaluating finished product texture, and economically by assessing process costs.

CHAPTER 2

Literature Review

2.1 Physicochemical Composition of Oats

Structure and Chemistry of Oat Kernel

It is important to understand oat grain characteristics and composition as well as how these are affected by the extrusion process design. The kernel has two main portions, the protective hull, and the oat groat. During oat milling and processing, the hull of the kernel is removed. The remaining oat groat can be classified as having three major components: the bran, the germ, and the starchy endosperm. Figure 2.1 illustrates a cross section of an oat kernel. Sections A, B, and C are higher magnifications of the bran, starchy endosperm, and germ-endosperm matrix, respectively (Webster and Wood 2011).

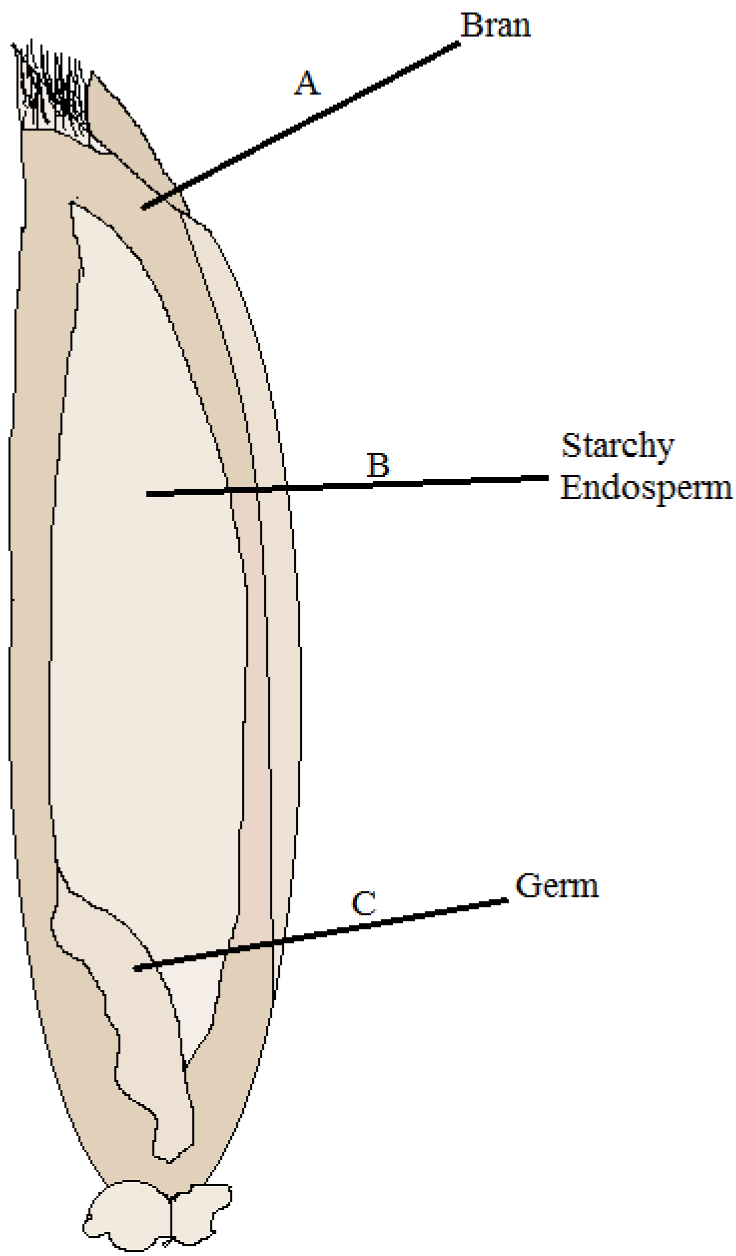

Figure 2.1 Cross section of oat kernel (Adapted from Webster and Wood 2011)

The bran, which is recognized as the outer layers of the groat, contains a large portion of the total available minerals (Peterson et al 1975; Frolich and Nyman 1988), vitamins (Fulcher et al 1981; Kent and Evers 1994), and antioxidants (Gray et al 2000; Peterson et al 2001). The endosperm is the region of the mature oat groat that primarily houses starch, proteins, lipids, and beta glucans. In most mature oat groats, there is a reverse gradient effect seen between protein and starch. In other words, protein and starch concentration are proportionally different in the outlayer of the endosperm versus the center of the endosperm (Webster and Wood 2011). The starchy endosperm can contain up to 90% of the total lipids found in oats. Most of the lipids found in the endosperm are neutral lipids, however there are small amounts of glycolipids and phospholipids. The endosperm cell wall is fortified with beta glucan, which is one of the non-starch carbohydrates found in the groat. The last major component of the oat is the germ, which primarily acts as an embroyo during germination. The germ is mainly composed of protein and lipid, with starch being a minor component (Webster and Wood 2011).

Oat Groat Physicochemical Composition

Extrusion processing is dependent upon several ingredient parameters, making it necessary to understand the chemical composition of oats. Table 2.1 shows the chemical composition of regular rolled oats:

Table 2.1 Composition of dry, not fortified regular rolled oats

Item	Moisture (%)	Protein (%)	Lipid (%)	Ash(%)	Carbohydrate(%)
Oats	10.8	13.2	6.5	1.9	67.7

Source: USDA National Nutrient Database 2015

The main components of oat groats which have an influential effect on extrusion are starch, protein, and lipids. Therefore, these components will be the focus of this review.

Starch

Starch is a major constituent to the total carbohydrate available in the oat groat. Typically, starch is found in the form of granules which are composed of several million highly branched amylopectin molecules as well as a larger amount of amylose molecules (Webster and Wood 2011) There is also a third component to starch called “intermediate materials”. Physicochemical and functional properties of the starch are dependent upon the variance in amylose, amylopectin, and intermediate materials (Wang and White, 1994). It is important to understand that every oat variety has diverse amounts of these starch components (Table 2.1).

There have been many studies performed on the use of corn, rice, and wheat starch over the last two centuries. However, oat starch was not extensively studied until the mid 1950s. In order to effectively process oats, one must truly understand the functionality and morphology of oat starch. Oat starch displays high water absorption activity as well as low gelatinization temperatures (Macarthur and D’Appolonia 1979). It has also been determined that cooked granules found in oat starches exhibit more sheer sensitivity than other cereal starches (Wang and White 1994). The starch found in oats significantly impacts the finished texture of the extruded oatmeal through the gelatinization process.

Starch Gelatinization

When both water and heat are applied to starch, a transition occurs in the structure of the molecules. Starch granules swell and collapse, becoming a mixture of polymers-in-solution. As heat is applied, there is increased motion of the molecules within the starch granule. This will eventually lead to the disruption of hydrogen and hydrophobic bonds for molecules found in the crystalline area of the granule. These molecules become hydrated and are discharged into the surrounding water. This process is known as gelatinization (Robyt 2008).

Starch gelatinization is an important physicochemical change which occurs in many food materials. There are varying types of starch such as corn starch, potato starch, rice starch, as well as oat starch. The gelatinization properties of each starch are slightly different (Ratnayake and

Jackson 2008). Each type of starch has a level of water and temperature which acts as the onset, peak, and conclusion of the gelatinization process. Figure 2.2 shows the effect of water content on gelatinization temperature in the example of rice starch. Generally, the lower the water to starch ration, the higher the temperature required to achieve complete starch gelatinization. According to Ratnayake and Jackson (2008), oats in excess water have an onset gelatinization temperature of 60°C, peak temperature of 63.5°C, and conclusion temperature of 70.5°C. The only other type of starch with lower gelatinization temperatures is wheat starch.

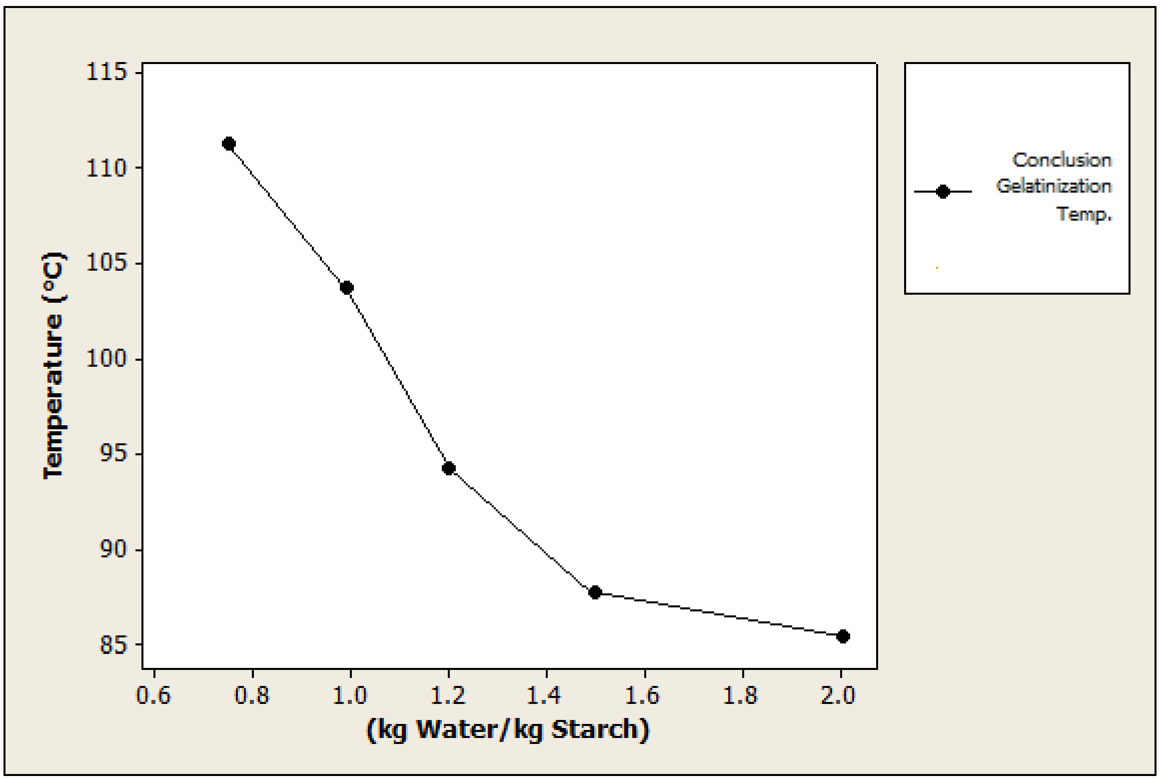

Figure 2.2 Relationship between water content and temperature for rice starch gelatinization (Adapted from Wirakartakusumah 1981)

Protein

The main role of protein in oats is its nutritional contribution accompanied by functionality during processing (Webster and Wood 2011). Proteins may coagulate and form a gel when exposed to high temperatures, but in the case of extrusion, a high enough temperature is not reached to cause gelation in the protein fraction. High thermal stability of oat globulin may be desirable in some settings. However, this functional property limits its use as a gelling agent in many food items processed at low temperatures. (Webster and Wood 2011)

Lipids

As mentioned previously, the lipid content of oats are about 7%. This is higher than in most other cereal grains (Decker et al 2013). The lipids in oats can create a lubrication effect, which reduces the shear force created inside the barrel of the extruder (Camire 2000). Therefore, processors will at times remove fat from the oats prior to extrusion to prevent this detrimental effect. Another important factor to consider during extrusion is lipid oxidation. The stability of oat lipids is compromised during exposure to the high temperatures to cook product. Therefore, temperature control is crucial to preventing rancidity in the finished product (Gutkoski and El-Dash 1998).

2.2 Influence of Other Ingredients

Sugar

The use of sugar as an ingredient in oatmeal plays the primary roles of sweetening and flavor enhancement. Brown sugar is one of the most widely used forms of sugar used in oatmeal processing. Brown sugar is made from blending granulated cane sugar with refinery syrups or molasses, but could also be granulated sugar which is artificially sweetened and colored to be similar to standard brown sugar (Stansell1997). Sugar helps prevent lumping in oatmeal by separating the starch molecules, which creates a desirable texture. Sugar also used to breakdown proteins so that they become more evenly dispersed in liquid mixtures (Canadian Sugar Institute 2015). In oatmeal processing, these functional properties play a significant role in ensuring effective dispersion of particles to aid in texture development.

Salt

Sodium Chloride, also known as table salt, is added to breakfast cereals such as oats to impart flavor to the product (Brady 2002). Salt intensifies the sweetness being contributed by natural and added sugar, and also helps reduce bitterness. Salt decreases the amount of available water in oatmeal mixtures, due to the hygroscopic nature of the ingredient. Starch gelatinization temperatures and times will increase due to the lower water activity in the product. It is essential to ensure that an appropriate amount of salt is added to the formula, as it has a direct impact on the functionality of other constituent ingredients (Hutton 2002).

Hydrocolloids

Gum as an ingredient can be sourced from exudates, seeds, or seaweed. The oatmeal formula used in this study utilized gum arabic (acacia), which comes from an exudate source. Acacia gum is regarded as one of the first thickening agents used in food products, and is widely used across the food industry in many applications. Emulsification, acid stability, low viscosity at high temperatures, binding properties, and impact on mouth-feel characteristics are the applicable functional properties of the gum arabic. In the extrusion process, high temperatures will be used to gelatinize the starch within the oat groat. The aforementioned properties of acacia gum will help ensure the product has a low viscosity and homogeneous texture within the barrel of the extruder, warranting effective mixing in the kneading zone of the barrel (Wareing 1999).

Flavors

Oats alone are generally regarded as having little flavor, and therefore the addition of some flavor enhancer is required. Oatmeal can be flavored with various types of additives to enhance the consumer experience. Some common flavors of oatmeal seen on the market are maple and brown sugar, strawberries and cream, cinnamon, as well as many more. The only added flavor affecting the process comes from spices such as cinnamon. Cinnamon is regarded as an aromatic spice, and the purpose of addition to the oatmeal is to provide flavor and odor to the finished product (Ranken 1997). One concern of the use of aromatic spices in the extrusion process is flavor retention. Due to the stress of temperature, shear force, and pressure on the mixture, flavors can degrade inside the barrel of the extruder (Maga1989). This degradation effect may lead some extrusion processors to add flavorings post extrusion, alleviating the detriments observed on flavor during extrusion.

Water

Water has a strong influence on the processing conditions as well as the flavor, texture, and appearance of ready to eat oatmeal. Controlling the moisture content of the feed has been proven to be a technique that can be used to regulate the temperature and flow rate during the process. The addition of water can also affect product rehydration, product density, and starch gelatinization (Harper 1981). Achieving starch gelatinization in oatmeal processing requires the addition of heat, shear force, and water. Water plays a major role in flavor retention in that, due to the reduced pressure relative to the product exiting the die, developed flavor that is water soluble will volatilize with the flashing of water. Therefore, it is essential to have an elongated die, so that the product has time to drop in temperature and decrease in pressure prior to entering the atmosphere (Maga 1989). The amount of water added during the process will be essential to creating uniformity in the finished extrudate (Harper 1981).

2.3 Ready to Eat Oatmeal

Human consumption of oat based products is significantly increasing due to their beneficial health implications. The range of oat based products for human consumption varies from cold cereals such as granola to hot cereals such as instant oats. Hot cereal is the most widely used application for oat flakes (Webster and Wood 2011). In order to comparatively determine the optimal unit operation for producing ready to eat oatmeal, it is important to assess the difference in the main product types. The table below illustrates the differences between hot cereal products, as well as the processing methodology for each.

Table 2.2 Different types of hot cereal products

Product Category[1]	Product Characteristics	Cooking Unit Operation	Finished Product Dispostion
Rolled Oats	-Prepare on the stovestop -Whole oat flakes -Addition of water required	Oats are steamed and then rolled thin	-Shelf Stable -Stovetop prepared
Instant Oatmeal	-Prepare-in-the-bowl -Fractionated oat flakes -Partially-gelatinized -Low moisture content -Addition of water to rehydrate starch -May be pre-portioned - Includes flavorings, additives, and vitamins	Oats are rolled into thinner flakes and/or steamed longer to pre-gelatinize the starch	-Shelf Stable -Microwave Prepared
Frozen Oatmeal[2]	-Pre-gelatinized -High moisture content -Pre-hydrated -Always pre-portioned - Includes flavorings, additives, and vitamins	-Evaporative Kettle Cooked -Product heated to gelatinization temperatures based on ingredient mix	-Frozen -Microwave Prepared

[1] Whole Grains Council. 2013.
[2] Wawona Frozen Foods. 2013.

The processing of oatmeal into a frozen unit using extrusion cooking is an unexplored method to achieve starch gelatinization for the frozen oatmeal product format.

Kettle Cooking

Developments in technology have led to manufacturing of instant oatmeal, (Table 2.2) making the product more convenient to consumers. While instant oatmeal has traditionally been packaged dry and requires the addition of water, prepared oatmeal can also be packaged into individually frozen ready to eat units. There is not a significant amount of available literature on the production of ready to eat oatmeal. However, processing information was provided from oatmeal industry contacts to aid in completing this study. Ready to eat units are made using the "kettle batch" method. These units have already been precooked with water, and require a microwave to make the product ready to eat. In the batch method, oatmeal is cooked inside of a kettle and then pumped into a piston filler. The piston filler then portions the oatmeal into individual units to be frozen (Figure 2.3) (Wawona Frozen Foods 2013).

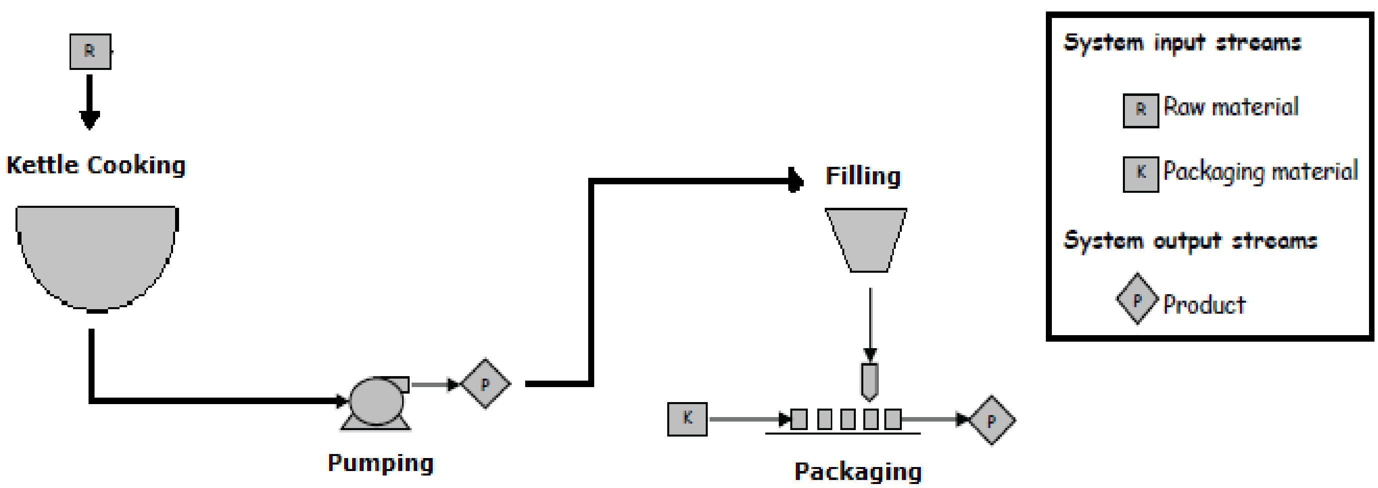

Figure 2.3 Schematic of kettle batch process for producing oatmeal (Adapted from Maroulis and Saravocos 2008)

The main disadvantages of the batch process are that it is inefficient due to the limitation of kettle size, as well as the difficulty in achieving the desired quality attributes with the equipment (Wawona Frozen Foods 2013). Oatmeal quality is primarily driven by the degree of starch gelatinization in the finished product (Tester and Karkalas 1996). The only mixing element available in the kettle is an impeller agitator or a scraped surface mixer, which are not effective in creating enough shear force to aid in starch gelatinization. A twin screw extruder offers more control during mixing and heating steps of food processing.

2.4 Extrusion Processing

Food extrusion is the process of forming or shaping raw material by forcing it through a restricted opening (Riaz 2000). Extrusion can further be described as starchy or proteinaceous materials that are thermomechanically processed under variable conditions to achieve a finished product (Guatam 1998). Extrusion is used in the food industry for a variety of benefits including low energy usage, low operational cost, high throughput capacity, and versatility (Harper 1981). Ready to eat breakfast cereals are one of the main products made using extrusion processing. Other products manufactured using extrusion processing are pet food and expanded ready to eat snack items such as corn puffs.

The applications for food extrusion systems include cold extrusion and hot extrusion, as well as low moisture extrusion (moisture content <40 %) and high moisture extrusion (moisture content > 40%). Cold extrusion is a low shear, room temperature process used mainly to form products such as pasta, candy, meat emulsions, and snack bars. Hot extrusion is a high temperature, high shear, and high pressure process used to cook and puff cereals and snack foods. Low moisture extrusion is commonly used for dry breakfast cereals (Akdogan 1999). However, for apparent reasons this process is not sufficient for the purposes of producing wet, ready to eat oatmeal. High moisture extrusion has been developed over the last ten years to meet the demand for products with high moisture content which needs to be cooked continuously and efficiently.

A food extruder has flighted screws which rotate inside of a temperature controlled barrel to function as a scraped surface heat exchanger (Choudhury and Gogoi 1995). Two types of food extruders which are currently used in the food industry include single screw and twin screw extruders. Single screw extruders utilize one single screw component which extends through the entire distance of the barrel, whereas twin screw extruders have two screws, either co-rotating or counter-rotating inside the barrel (Riaz 2000). Twin screw extruders can also have either intermeshing or non-intermeshing screws. Intermeshing screws have shared channels of conveyance, whereas non intermeshing screws do not engage each other's threads (Riaz, 2000). Twin screw extrusion is a highly versatile process capable of producing a wide variety of products in comparison to the single screw models. In contrast to a single screw system, twin screws are able to handle viscous, sticky, wet materials which would not flow in a single screw system. Also, twin screw extruders allow for a wide range of particle size whereas single screw models are limited to a specific range (Riaz, 2000).

2.5 High Moisture Extrusion

High moisture extrusion has been made possible with the implementation of a twin screw system, new barrel designs, and versatile screws and dies (Akdogan 1999). The extruder conditions that impact product qualities are screw speed, throughput, temperature, screw configuration, die design, and barrel ratios. The extruder conditions as well as ingredient composition impact finished extrudate quality. Feed moisture and lipid content play a significant role in the characteristics of starch based extrudates, such as oatmeal (Nguyen and others 2010).

Figure 2.4 illustrates how process parameters influence the finished products of high moisture extrusion.

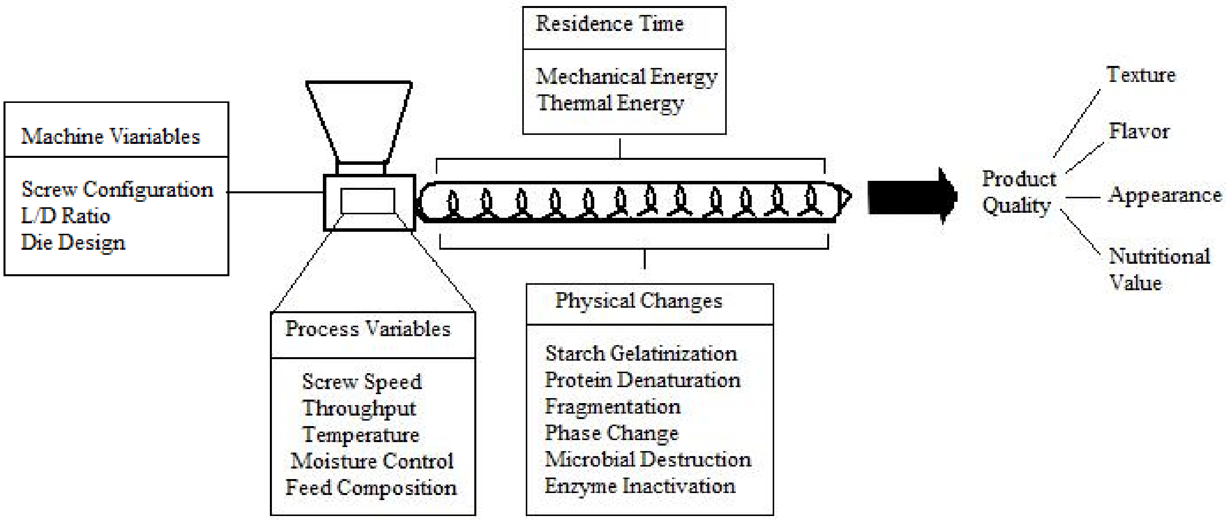

Figure 2.4 Schematic of extrusion processing paramters (Adapted from Choudhury and others 1995)

One application for high moisture extrusion has been the production of texturized proteins. Examples of products made using this process are extruded crab analog and texturized soybean foods such as fupi (Shen and Wang 1992). Protein extrudate quality attributes are affected by extrusion processing conditions, pH, and the nature of the ingredients being used. Usually, these types of products are manufactured using the direct injection of water as opposed to pre-hydration of the mix (Akdogan 1999). Protein structures are transformed under high pressure, shear, and temperature throughout the extrusion process (Harper 1981). One study found that extrusion barrel temperature was the most influential processing condition on finished product texture for dehulled whole soybean (Hayashi and others 1992). Akdogan and others (1997) determined that the design of the die plays an influential role on finished product texture for protein based products. In order to achieve the proper elasticity and fluidity required for texturization, a die which provides a cooling effect is required (Noguchi 1989). This cooling effect allows the protein in the food matrix to maintain air bubbles, creating a layered texture similar to that of meat (Harper 1981).

High moisture extrusion is desirable for starch based products due to the potential for complete starch gelatinization of the extrudate. It is important that the starch is gelatinized because it is more susceptible to enzymatic reactions in that state. Extruders are analogous to enzymatic bioreactors. The viscosity of the product is greatly reduced when enzymatic reactions are coupled with mechanical and thermal breakdown of starch. In the early 1970s, it was discovered that the use of high moisture extrusion could inhibit enzymatic reactions in breakfast cereals. This led to further studies of enzymatic reaction prevention in other applications, such as the fish processing industry (Choudhury and others 1995). In order for a twin screw extruder to be used effectively to influence enzymatic starch hydrolysis, product temperature, pH, and enzyme concentration must be considered (Akdogan 1999). While these experiments found that high moisture extrusion is a useful new method to influence enzymatic reactions in starch based products, overall, little research exists on other starch interactions using this process.

2.6 Process Economics: Extrusion Processing

Economic Advantages of Extrusion Processing

There has been little research performed to determine if high moisture extrusion methods would be a viable option to produce oatmeal. However, extrusion allows for a continuous, efficient process and is regarded as an effective method to produce many ready to eat products. This is primarily due to the fact that extrusion cooking combines unit operations such as pumping, mixing, kneading, heating, and forming in one machine (Jansen 1989). Also, the amount of floor space required by an extrusion system is significantly less than that of traditional cooking operations (Riaz 2000). Processing costs are also lower than typical cooking and forming systems. Darrington (1987) reported savings in raw materials (19%), labor (14%), and capital investment (44%) when implementing extrusion.

Process Costing

Process costing is utilized for product pricing when a department within a company manufactures individual units of output that are the same. In using this assessment tool, costs are consistently accumulated by department over a certain period of time. The costs are then assigned uniformly to all units which were produced during that time period. One tactic used to assign costing to units is called weighted average costs. This method applies aggregated costs to produced units by dividing the total cost with the number of units produced during the period being assessed (Garrison and others 2012).

Extrusion Process Costing

In order to determine the feasibility of using extrusion for ready to eat oatmeal, it is important to understand the process costs associated with extrusion. Due to the fact that extruders are usually a part of a large plant with multiple processing lines and products, the initial apportioning of costs to an individual extruder can be cumbersome. One tactic to alleviate the difficulty in assessing operating costs is to monitor the extrusion line for a given period of time and track all variable costs as a function of production (Harper 1981). Figure 2.5 displays a representative cost flow for an extrusion process, outlining all of the factors to consider when determining manufacturing costs for an extrusion process.

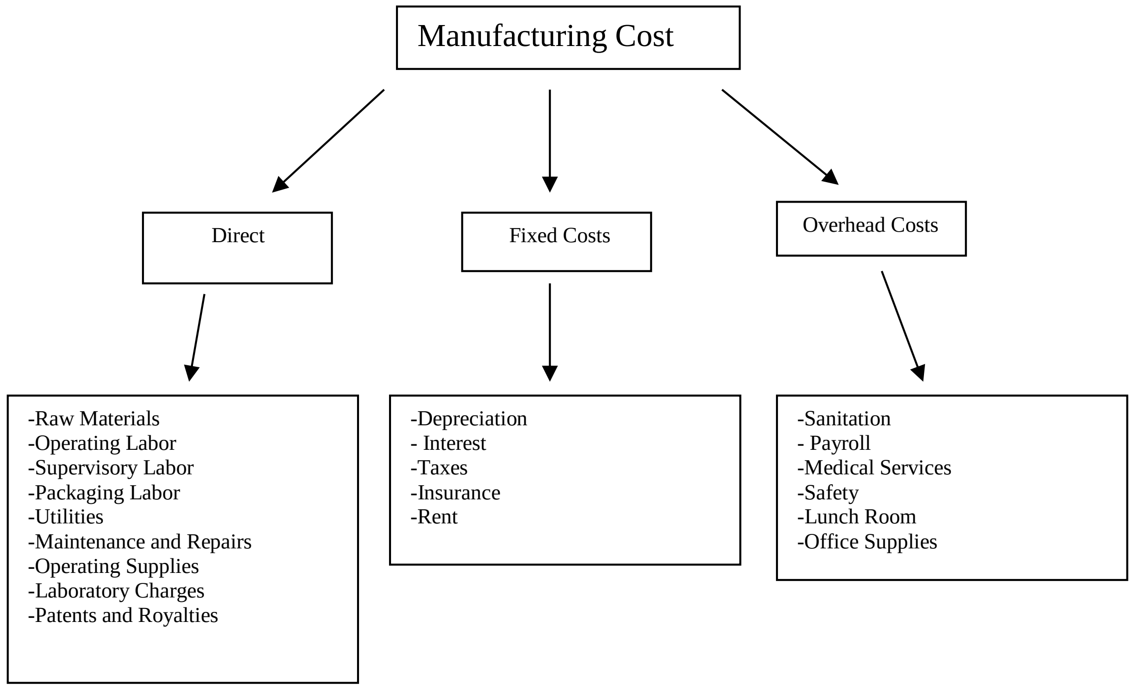

Figure 2.5 Production cost sheet for an extrusion process. (Adapted from Harper 1981)

In a typical extrusion process, the cost breakdown is as follows: raw materials are about 35 to 60 % of total cost, labor 5 to 10%, packaging costs 25 to 50%, utilities 5 to 10 %, and all other costs about 5% (Harper 1981). When developing a business strategy around implementing an extrusion process, these are the expected values which could be used to predict final product cost.

Functional and nutritional properties of oats serve as a gateway to the development of new oat-based products. An understanding of how these qualities will be influenced by processing variables is critical to using the extrusion technology application for oatmeal. Processing parameters will ultimately play a role in the finished product quality. The process costs of extrusion technology are substantial. However, due to the high throughput capacity of the machine coupled with the benefits of continuous methodology, it could be an optimal technology for large scale food producers. Most studies on high moisture extrusion have focused on protein based products. This study will attempt to apply the high moisture technique to a starch based extrusion system, and determine feasibility through measuring technical and economical metrics.

CHAPTER 3

Materials and Methods

Table 3.1 and 3.2 outline the various materials and equipment used throughout the experimentation:

Table 3.1 Materials used in study

Materials	Supplier	Function	Experiment
Rolled Oats- 10-20124	Honeyville Food Products 1080 N Main Ste 101 Brigham City, UT 84302	Base Ingredient	Pilot Study and Experiments 1, 2, 3
Acacia Gum	TIC Gums 10552 Philadelphia Rd White Marsh, MD 21162	Stabilizer	Experiments 4, 5, and 6
Granulated Cane Sugar	Sysco Corporation 1390 Enclave Parkway Houston, TX 77077	Sweetener	Experiments 4, 5, and 6
Granulated Kosher Salt	Sysco Corporation 1390 Enclave Parkway Houston, TX 77077	Flavor Enhancer	Experiments 4, 5, and 6
Water	Cal Poly State University 1 Grand Ave San Luis Obispo, CA 93407	Hydration	Experiments 4, 5, and 6
Frozen Oatmeal Control	Wawona Frozen Foods 100 Alluvial Ave Clovis, CA 93611	Hydration	Experiments 4, 5, and 6

Table 3.2 Equipment used in this study

Equipment	Source	Purpose	Experiment
Clextral Twin Screw Extruder- Model EV	Clextral Firminy Cedex,	Cooking/Mixing/Portioning	All Experiments

Table 3.2 (Cont'd). Equipment used in this study

25	France		
Hobart Vertical Chopper Mixer - Model HMC450	Hobart Corporation 701 S Ridge Ave Troy, OH 45373	Size reduction	Experiment 5 and 6
Scale (g) Model: ARD110 SN: H2831203250986 P	Ohaus Corp. 19A Chapin Rd. Pine Brook, Morris, NJ 07058	Weighing product	All Experiments
Blast Freezer	Cal Poly State University 1 Grand Ave San Luis Obispo, CA 93407	Freezing	All Experiments
Microwave Oven Model : PEB1590DM2BB	General Electric 3135 Easton Turnpike Fairfield, CT 06828	Thawing/Reheating	All Experiments
Clextral Super K PP8 Water Pump	Clextral Firminy Cedex, France	Extruder water addition	Pilot Study and Experiments 1, 2, 3, 4, and 5
OMNI DC2A2AP Metering Pump	Novatech USA 800 Rockmead Dr Ste 102 Kingwood, TX 77339	Extruder water addition	Experiment 6
Compa Chill – Chiller Model: SA3-4-2PT	Whaley Products, Inc 526 Charlotte Ave Burkburkett, TX 76354	Extrusion cooling	All Experiments
Texture Analyzer Model: TAXT Plus SN: 11460	Texture Technologies Corp. 18 Fairview Road Scarsdale, NY 10583	Measuring texture	All Experiments

The following methodologies were consistently used in all experimentation:

Extrusion Parameters

All experiments were conducted using a co rotating, intermeshing, self- wiping twin screw extruder (Model EV 25, Clextral, Firminy Cedex, France). It was equipped with modular barrels, each 100mm long, and bored with two 25 mm diameter holes. The twin screws had segmental screw elements, each 25 or 31 mm in length, so that reverse screw elements could be placed at a desired location along the length of a splined shaft. Thermal energy was provided by induction heaters mounted on 100 mm barrel sections. Extruder length was 1000 mm with a length to diameter ratio of 32:1. A customized 19mm diameter die was used. The die had a total length of 50 mm, with curvature occurring at a 45° angle to aid in vertical filling of container (Figure 3.2). Material was fed into the extruder inlet port by a twin screw metering feeder. Screw speed, material feed rate, water injection rate, and barrel temperatures were monitored from a control panel on the side of the extruder (Figure 3.1).

Figure 3.1 Clextral Model EV 25 Twin Screw Extruder (Source: Clextral, Inc.)

Figure 3.2 Die Configuration

Barrel Temperature Profile

The barrel of the extruder has 10 sections in total. (Figure 3.3) As the feed is being forced through the barrel by the twin screws, various temperature set points will be in place to optimize starch gelatinization and overall mixing efficiency. The sections of the barrel will be classified into 3 larger zones that follow a sequential process. In the initial zone, called the "conveying zone", the oatmeal will be conveyed from the feeder to the reaction zone. This will include subzones 1 through 5. In this zone, temperature will rise slowly before an optimal mixing temperature is reached. Subzones 6 and 7, the "reaction zone", will have a screw profile that allows for product to be kneaded and dispersed while being heated. The primary cooking of the product will also take place in this zone. The reaction zone will have an optimal temperature in which starch gelatinization will take place within the barrel. The final "cooling zone" will have temperatures slightly dropping as the pressure in the chamber is increased. These last 3 subzones will aid in creating a consistent, viscous texture in the product. The temperature profile for the experiment is displayed in Figure 3.3. The temperature settings will remain in the same sequence for each trial being tested. Optimal barrel temperature profile for extrusion of oatmeal will be determined once the results are correlated with finished product quality. Prior to changing any of the machine parameters, the extruder was run for at least 3 minutes at steady state to allow for equilibrium to be reached.

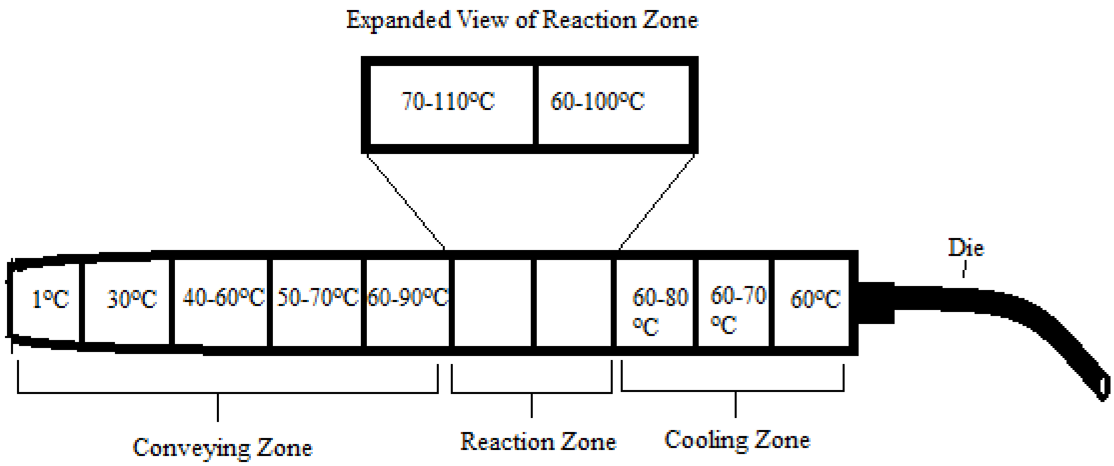

Figure 3.3 Barrel Temperature Profile for Oatmeal Study

Screw Profile

In order to remove the variable of screw profile, the twin screws were setup the same way throughout the various phases. (Figure 3.5) The" conveying zone" will have standard screw components (C2F) to feed the product through the barrel. The "reaction zone" will utilize mixing components (BL 22 and C1F) that will be used to knead the product and assist in mechanically breaking down starch granules to allow for gelatinization. The "cooling zone" will primarily have standard components (C2F) which feed the cooked product to the die for filling. (Figure 3.4) Die configuration remained the same throughout all three phases of the experiment. (See Figure 3.2)

Figure 3.4 Screw segments used in screw profile design (Source: Clextral Inc.)

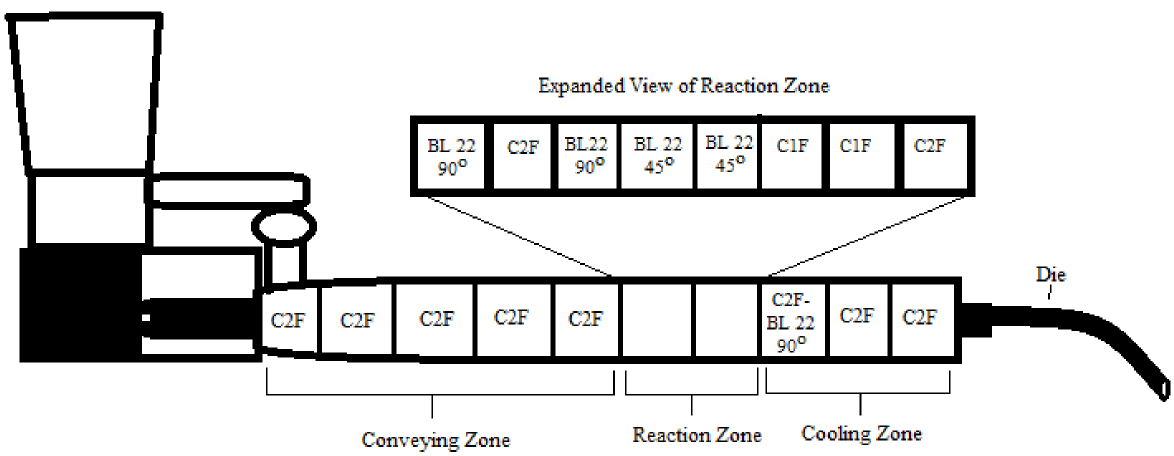

Figure 3.5 Screw profile design for oatmeal study showing location of various elements.

Water Rate Adjustment

The amount of water directly injected into the barrel of the extruder was fed using the Clextral Super K PP8 diaphragm pump, with the exception of Experiment 6. This final experiment utilized a Novatech OMNI DC2A2AP model pump for feeding. Figure 3.6 portrays both types of pumps and the associated operational specifications.

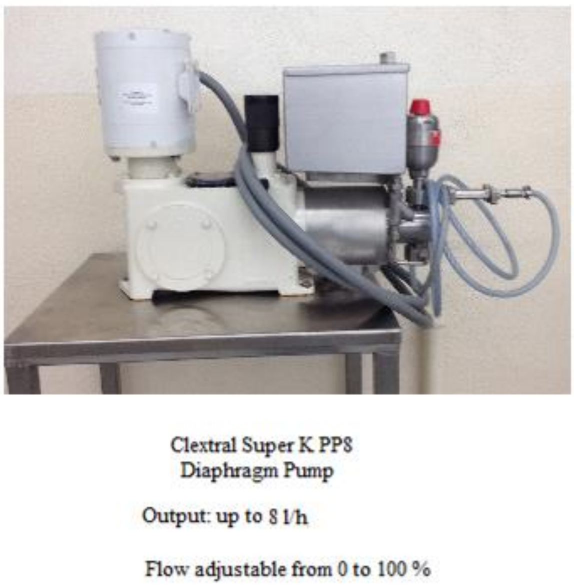

Figure 3.6 Water Pumps used in oatmeal study (Clextral, Inc. and Novatech USA)

Water Port Location

Both the Clextral Super K PP8 and the Novatech OMNI DC2A2AP had interchangeable outlets to be connected to any of the ten barrel zones. During Experiment 3, the Super K PP8 was setup to directly inject water into the two main mixing zones of the extruder, zones 4 and 5. For all other Experiments, water was injected into the port on zone 2. (Figure 3.7)

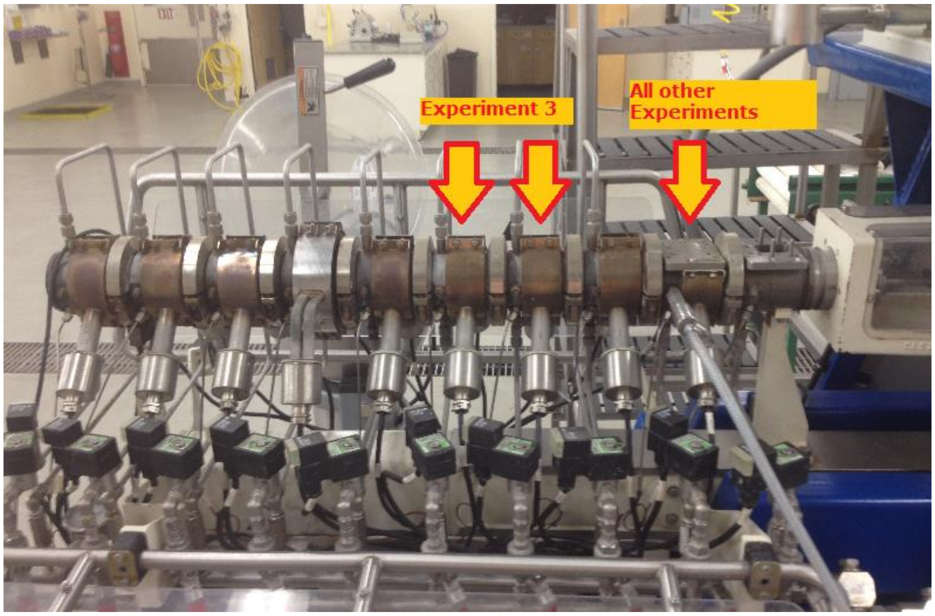

Figure 3.7 Water Port Location Schematic

Feed Preparation

For the pilot study and Experiments 1, 2, and 3, rolled oats were added directly to the hopper of the extruder. No special preparations of any kind were performed on the raw materials. The feasibility study section provides information of the methodology used for the addition of other ingredients in Experiment 4 and particle size reduction in Experiments 5 and 6.

Sampling

Each sample was collected from extrusion die and packaged into an air tight plastic container. The container was then placed into a walk in freezer with a temperature of -20°F and allowed to freeze overnight.

Product Analysis

The following section details the analysis of the textural properties of the extruded oatmeal.

<u>Sample Preparation</u>

Samples were taken from freezer and heated in a microwave as follows:

1) Microwaved on high setting with lid propped on top of container for 1.5 minutes

2) Sample then removed, stirred with a fork for approximately 10 seconds

3) Sample placed back into microwave for 2-2.5 minutes

4) Sample removed and underwent a final stir for approximately 10 seconds

After the products were finished the microwave step, they were allowed to cool to between 7-10°C. Once proper temperature was reached, 100 grams of sample was weighed for testing. Sample texture was measured using the TA.XT Plus Texture Analyzer (Texture Technologies Corp, Scarsdale, N.Y., USA).

Textural Properties

The force required to back extrude the oatmeal mixture was determined by placing 100 grams of sample into the TA-94 back extrusion rig (Texture Technologies Corp, Scarsdale, N.Y., USA). The rig is comprised of a cylindrical sample container which is centrally located underneath a disc plunger (Figure 3.8). When a test was initiated, the disc plunger was lowered into the receptacle full with product. A 30 second compression test was performed which extrudes the product up and around the edge of the disc. This compression test provided results which were relative to product viscosity. Data was recorded using Microsoft Excel, to be further analyzed at a later time (Stable Micro Systems 2003).

Figure 3.8 TA-94 Back Extrusion Rig used in oatmeal study

Experimental Methodology

The study was completed in three phases: a preliminary pilot study, the main experiment (Experiment 1) followed by a series of feasibility studies. Experiment 1 focused on the use of regular rolled oats as the only ingredient, and the extruder was tested for differences on final product when adjusting the feed rate, water addition rate, and barrel temperature profile. An ideal product was not achieved in the preliminary research, and therefore the feasibility studies were performed in an attempt to subjectively test for the effect of other extrusion parameter adjustments. Table 3.1 displays the processing parameters which were used throughout experimentation.

Table 3.3 Overview of High Moisture Extrusion Experiment Operating Parameters

	Zone 6 Temp (°C)	Zone 7 Temp (°C)	Feed Rate (Kg/hr)	Water Rate (Kg/hr)	Formula	Screw speed (RPM)	Particle Size	Water Injection Port Location
Pilot Study	90-100	80-90	6	7-8	WRO[1]	450	WOG[2]	2
Experiment 1	70-110	60-100	6-10	6-8	WRO	450	WOG	2
Experiment 2	100	90	6	8	WRO[1]	450-900	WOG[2]	2
Experiment 3	100-110	90-100	6-7	6-8	WRO	450-650	WOG	4-5
Experiment 4	100	90	6	6-8	FIM[3]	450	WOG	2
Experiment 5	100	90	6	8	FIM	450-550	RPS[4]	2
Experiment 6	100	90	6	10.4-13.2	FIM	450	RPS	2

[1] Whole Rolled Oats, [2]Whole Oat Groats, [3]Formula Ingredient Modification, [4]Reduced Particle Size

<u>Extrusion Adjustment Bias</u>

One important aspect of the experimental methodology is that in each experiment, the extruder was not fully shut down and restarted back up again to test each treatment. Therefore, it is possible that some bias occurred in the first treatments performed in each experiment due to the difference in environmental conditions between the first treatments and succeeding ones.

3.1 Preliminary Experiment

The goal of the pilot study was to determine the overall technical feasibility of processing ready to eat oatmeal using high moisture extrusion. Feasibility was based off of the quality of the finished product and the capability of the extruder to produce the oatmeal without any equipment malfunctions or product defects.

Table 3.4 Extrusion Parameter Settings for Pilot Study

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp (°C)
1	1	30	60	70	80	90	80	70	60	60
2	1	30	60	70	80	90	80	70	60	60
3	1	30	60	80	90	100	90	80	70	60
4	1	30	60	80	90	100	90	80	70	60

Trial	Water Rate (kg/hr)	Feed Rate (kg/hr)	Screw Speed (rpm)
1	8	6	450
2	7	6	450
3	8	6	450
4	7	6	450

3.2 Main Experiment (Experiment 1)

The goal of Experiment 1 was to determine what impact, if any, that reaction zone temperature, feed rate, and water addition rate had on finished product texture. The overall feasibility of extrusion to produce the oatmeal was also evaluated. For simplicity in labeling, capital letters relating to the parameter and the value of the parameter was used: Letter 1 – Temperature Profile, Letter 2 – Water Profile, Letter 3 – Feed Profile, L = Low, M = Medium, H = High.

- Ex: LML = Low Temperature Profile, Medium Water Profile, Low Feed Profile

Table 3.5 Extrusion Parameter Settings for Main Experiment

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp. (°C)
Low	1	30	40	50	60	70	60	60	60	60
Medium	1	30	60	70	80	90	80	70	60	60
High	1	30	60	70	90	110	100	80	70	60

Trial	Water Rate (kg/hr)	Feed Rate (kg/hr)
Low	6	6
Medium	7	8
High	8	10

3.3 Feasibility Studies

After performing the main experiment, it was determined that more testing needed to be performed to subjectively measure the feasibility of high moisture extrusion as a method of producing oatmeal. A new series of qualitative testing was carried out in an effort to see how other processing parameters factors may play a role in creating an ideal finished product.

3.3.1 Experiment 2- Screw Speed

Screw Speed Adjustment

The objective of Experiment 2 was to determine if changing the screw speed would at all yield better finished product quality. The Clextral extruder ran at ten different levels of screw speed, ranging from 450 rpm to 900 rpm.

Table 3.6 Extrusion Parameters for Experiment 2

Trial	Screw Speed (RPM)	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp . (°C)	Zone 6 Temp . (°C)	Zone 7 Temp . (°C)	Zone 8 Temp . (°C)	Zone 9 Temp . (°C)	Zone 10 Temp . (°C)
1	450	1	30	60	80	90	100	90	80	70	60
2	500	1	30	60	80	90	100	90	80	70	60
3	550	1	30	60	80	90	100	90	80	70	60
4	600	1	30	60	80	90	100	90	80	70	60
5	650	1	30	60	80	90	100	90	80	70	60
6	700	1	30	60	80	90	100	90	80	70	60
7	750	1	30	60	80	90	100	90	80	70	60
8	800	1	30	60	80	90	100	90	80	70	60
9	850	1	30	60	70	80	90	80	70	60	60
10	900	1	30	60	70	90	110	100	80	70	60

3.3.2 Experiment 3- Water Addition Location

Experiment 3 was performed in an effort to determine if changing the location in which the water was injected into the barrel would improve the efficacy of the process to make high quality product.

Water Port Location

Throughout the various treatments, the Clextral water pump was setup to directly inject water into the two main mixing zones of the extruder, zones 4 and 5 (Figure 3.7) .

In order to try and get an indication of the effect that previously tested factors had in conjunction with water location, feed rate, water rate, reaction zone temperature, and screw speed were also tested during this experiment.

Table 3.7 Extrusion Settings for Experiment 3

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp. (°C)
A	1	30	60	80	90	100	90	80	70	60
B	1	30	60	70	90	110	100	80	70	60
C	1	30	60	80	90	100	90	80	70	60
D	1	30	60	80	90	100	90	80	70	60
E	1	30	60	80	90	100	90	80	70	60

Trial	Water Rate (kg/hr)	Feed Rate (kg/hr)	Screw Speed (RPM)	Water Zone Entry
A	6	6	650	4
B	7	6	450	4
C	8	6	450	4
D	7	6	450	5
E	7	7	650	5

3.3.3 Experiment 4- Oatmeal Mix

Thus far, only regular rolled oats were used as feed. The objective of this experiment was to evaluate whether or not adding in the same functional ingredients found in the control product would aid in texture development.

Feed Preparation

5 kg of the following mix was hand stirred with a whisk and then run through the extruder at the stated parameters:

- 59.50% Regular rolled oats
- 28.50% Sugar
- 10.40% Acacia Gum
- 1.50% Salt

Table 3.8 Extrusion Settings for Experiment 4

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp. (°C)
A	1	30	60	80	90	100	90	80	70	60
B	1	30	60	80	90	100	90	80	70	60
C	1	30	60	80	90	100	90	80	70	60
A2*	1	30	60	80	90	100	90	80	70	60

Trial	Water Rate (kg/hr)	Trial	Feed Rate (kg/hr)	Trial	Screw Speed (rpm)
A	8	1	6	1	450
B	6	2	6	2	450
C	7.5	3	6	3	450
A2*	8	4*	6	4*	450

*Trial A2 occurred at the end of the run with the same parameters as Trial A

3.3.4 Experiment 5- Reduced Particle Size

The goal of Experiment 5 was to determine the effect of reducing the particle size of the regular rolled oats, therefore increasing the surface area of the starch regions inside the oat groat.

Feed Preparation

Five kilograms of regular rolled oats were blended for 5 minutes by a Hobart HCM 450 Cutter Mixer (Hobart Corp, Troy, Oh., USA), on the high setting. The ground oats were then used as feed, and added to the hopper of the extruder (Figure 3.9).

Figure 3.9 Feed Preparation using Hobart HCM 450

Extrusion Parameters

Table 3.9 Extrusion Settings for Experiment 5

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp. (°C)
A	1	30	60	80	90	100	90	80	70	60
B	1	30	60	80	90	100	90	80	70	60
Trial	Water Rate (kg/hr)		Trial	Feed Rate (kg/hr)		Trial	Screw Speed (rpm)			
A	8		1	6		1	450			
B	8		2	6		2	550			

3.3.5 Experiment 6- New Water Pump

The goal of Experiment 6 was to determine the effect of changing the water injection rate to higher levels than previously attempted. The Novatech Omni pump was used for this experiment.

Feed Preparation

Five kg of the following mix was homogenized in a Hobart HCM 450 Cutter Mixer for 3 minutes then run through the extruder at the stated parameters:

- 59.50% Regular rolled oats (pre-blended for5 minutes in Hobart KCM 450)
- 28.50% Sugar
- 10.40% Acacia Gum
- 1.50% Salt

Extrusion Parameters

Table 3.10 Extrusion Settings for Experiment 6

Trial	Zone 1 Temp. (°C)	Zone 2 Temp. (°C)	Zone 3 Temp. (°C)	Zone 4 Temp. (°C)	Zone 5 Temp. (°C)	Zone 6 Temp. (°C)	Zone 7 Temp. (°C)	Zone 8 Temp. (°C)	Zone 9 Temp. (°C)	Zone 10 Temp. (°C)
A	1	30	60	80	90	100	90	80	70	60
B	1	30	60	80	90	100	90	80	70	60
C	1	30	60	80	90	100	90	80	70	60
Trial	Water Rate (kg/hr)		Trial	Feed Rate (kg/hr)		Trial	Screw Speed (rpm)			
A	10.4		A	6		A	450			
B	13.2		B	6		B	450			
C	12		C	6		C	450			

Technical Evaluation Assumptions

- Clextral Extruder operates consistently when performing the experiment.
- The environmental conditions of the Pilot Plant do not change between trials.
- The oats supplied by Wawona were all grown, harvested, and processed under the same conditions

3.3.6 Process Economics Evaluation

The process economics of the extrusion method to produce oatmeal will be assessed using the following parameters:

1) Capital Requirements
2) Process Costing
3) Net Present Value

In their text, Food Plant Economics, Maroulis and Saravacos (2008) surveyed the food processing industry and determined average financial requirements for various processing technologies. For the purposes of evaluating the economical requirements for the auxiliary blending and feeding process, financial data was generalized from this collection of data. Extrusion financial data was extrapolated from the process performed in the Cal Poly Pilot Plant and applied to the following model for commercially utilizing high moisture extrusion to process oatmeal:

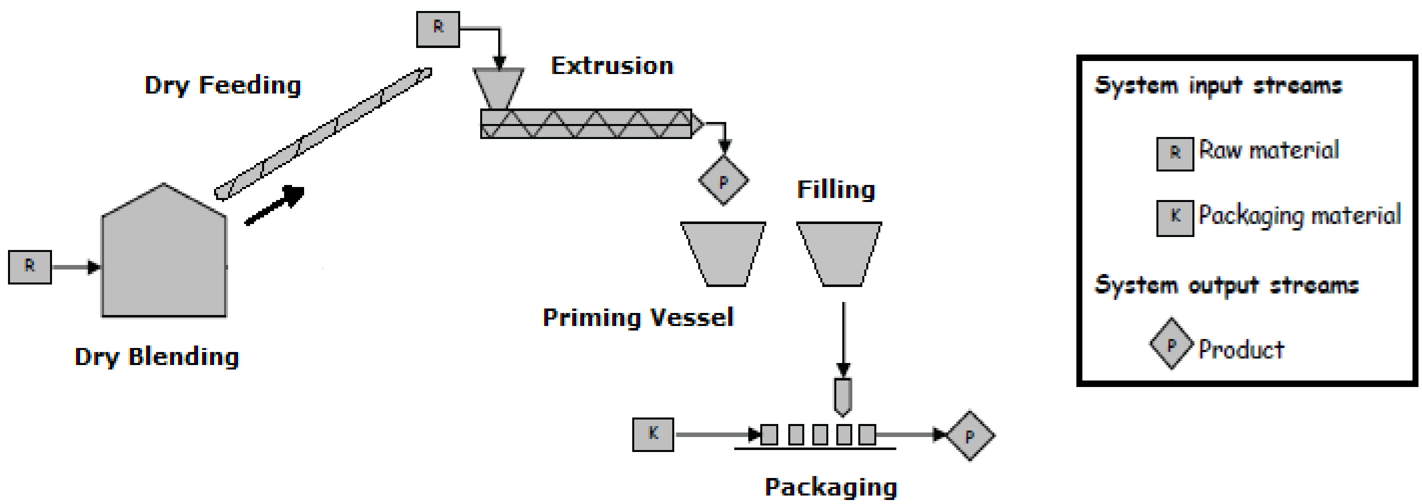

Figure 3.10 Process Flow Diagram for High Moisture Extrusion of Oatmeal (Adapted from Maroulis and Saravocos 2008)

Capital Requirements

Capital costs will be calculated and amortized based on the following expenditures:

1) Processing Equipment Cost
   a. Dry Blending (Ribbon Blender)
   b. Dry Feeding (Screw Conveyor)
   c. Extrusion
2) Packaging Equipment Costs

Depreciation will be calculated using the following formula:

Total Capital Expense ($) / 20 year lifespan / 12 months per year = Monthly Depreciation Expense

Process Cost Analysis

The process costing analysis will include an evaluation of all expenses associated with the production of 100,000 pounds per month. Table 3.9 summarizes how the costs of goods available for sale will be allocated.

Table 3.11 Cost of Goods Available for Sale

Line Item	Formula
Direct Production Costs	
Raw Ingredients	(Rolled Oats (lbs) x $.05/lb)[3] + (Gum (lbs) x $5.20/lb)[4] + (Sugar (lbs) x $.24/lb) [5] + (Salt (lbs) x $.16/lb) [6] x .95 (for a 5% waste estimation)
Packaging Material	$0.15 x Total Units
Processing Labor	Man Hours Worked x $15/hour
Packaging Labor	Man Hours Worked x $15/hour
Supervisory Labor	$6,000 monthly salary x .33 (responsible for 3 processing lines)
Utilities	Energy Utility Cost + Non Energy Utility Cost Energy Utility Cost = Electricity (purchased) + Steam + Cooling Water Reference crude oil price of 67 $/bbl1 Electricity= (Total # of kWh) X ($.105/kWh) 1 Cooling Water = (Total Well Water Usage in m3) x ($ 0.281/ m3) 1 Non Energy Utility Cost = Process Water Process Water = (Total Potable Water Used in m3) x ($0.50/ m3) 1
Maintenance Labor	Man Hours Worked x $20/hr
Maintenance Supplies	Price for Spare Parts
Fixed Charges	
Depreciation	Total Capital Expense ($) / 20 year lifespan / 12 months per year = Monthly Depreciation Expense

[3] Maroulis and Saravacos 2008
[4] TIC Gums
[5] International Monetary Fund, April 2015
[6] Sysco Corporation

Table 3.11 (Cont'd) Cost of Goods Available for Sale

Overhead Costs @5%
Total Costs
Cost per Pound of Oatmeal
Cost per 4 oz Unit

Process Costing Weighted Average Formula

Total Cost of Goods Available for Sale / Total Units Available for Sale = W.A. Cost per Pound

Supplemental Formulas

Throughput Capacity: 100,000 pounds / 500 lbs/ hour = 200 hours of run time

16 oz oatmeal= 4 finished product units @ 4 ounces each

Net Present Value (NPV) Analysis

A Net Present Value Analysis will be performed to measure the profitability for a company to implement the high moisture extrusion system.

NPV Formula

Σ ((Net Period Cash Flows/ $(1+ R)^t$) – Initial Investment) + (Salvage Value/ (1+R)^t))

R= Discount Rate

t= Number of time periods

Economic Evaluation Assumptions

I. Infrastructure

a. The facility implementing oatmeal production already has typical utilities installed in the building as well as chilled water

b. There is already a building infrastructure in place

c. Processing supplies such as buckets, utensils, carts, etc. are available within facility

II. Costing

a. Fixed costs such as insurance, interest, and taxes do not change relative to oatmeal processing methodology

b. Cash is used to purchase all necessary infrastructure

CHAPTER 4

Results and Discussion

4.1 Process Economics Evaluation

Process Costing

Table 4.1 Cost of Goods Available for Sale

Line Item	Amount ($)[1]
Direct Production Costs	
Raw Ingredients	63,615
Packaging Material	45,000
Processing Labor	3,000
Packaging Labor	3,000
Supervisory Labor	1,980
Utilities	6,489
Maintenance Labor	4,000
Maintenance Supplies	8,000
Fixed Charges	
Depreciation	4,354
Overhead Costs @5%	6,972
Total Costs	146,410
Cost per Pound of Oatmeal	1.46/ pound
Cost per 4 oz Unit	0.37/each

[1] See page 43 for formulas used to calculate values

While the capital expenditures for the system are high (Table 4.2), due to economies of scale the unit cost is reasonably low. One pound of ready to eat oatmeal will likely be portioned into four finished units. Therefore, the price of $1.44 per pound then becomes $0.37 per unit. This number is relatively low and comparable to other ready to eat frozen meals currently in the market place. In order to illustrate the comparability of the extruded ready to eat oatmeal with other products, industry firms would need to divulge privileged information such as typical processing costs. Unfortunately, this information is not typically released. However, it can be estimated that one unit of ready to eat oatmeal would wholesale between $0.80 and $0.90 cents. With a standard 35% retail markup, one unit would sell at a price between $1.08 and $1.21. Realistically, the product would sell in a multipack with 2 units, and be priced between $2.79 and $2.99. These are retail values which align with similar product currently being sold on the market.

Capital Expenditures

Table 4.2 Capital Requirements for High Moisture Extrusion System

Component	Estimated Cost ($)	Function	Source
Twin Screw Extruder	1,000,000	Cooking	Clextral
Ribbon Blending Unit	15,000	Dry Mixing, Conveying	Conveyor Engineering
Incline Screw Conveyor	30,000	Metering, Conveying	Conveyor Engineering
Piston Filler	35,000	Packaging	Simplex Fillers
Labeler	20,000	Packaging	Alibaba
Total:	1,100,000		

The capital expenditures required to implement the extrusion process are significant. Other cooking methodologies use equipment which range in cost between $25,000 and $100,000, and are capable of producing the same product. As mentioned previously, one of the main advantages of the high moisture extrusion system is that the throughput capacity is higher through continuous processing. This aspect of the technology plays a role in enabling the net present value of the system to be nearly double the initial investment (assuming a 4% discount rate). Table 4.3 displays various scenarios which take the inflation of the dollar into account at 4, 4.5, 5, 5.5, and 6 % discount rates. Worst case scenario, the firm will profit nearly $650,000 from using this technology over the course of 20 years. Best case scenario, the company would make $950,000 or almost $47,170 of discounted revenue each year for the 20 year period. Depending on the size of the company and operation, these numbers could be acceptable. If a firm was to move forward in purchasing the extruder, it would be advantageous to use it for more than one product platform, therefore further increasing the NPV. Overall, while the cost of the high moisture extrusion system is considerably high, purchasing can be justified through the difference in production economies of scale, a prompt return on investment, and a significantly positive net present value.

Table 4.3 Net Present Value for High Moisture Extrusion System

Discount Rate	**0.04**	**0.045**	**0.05**	**0.055**	**0.06**
Initial Investment	$1,100,000	$1,100,000	$1,100,000	$1,100,000	$1,100,000
Revenue, Year 1-20[1]	$143,640	$143,640	$143,640	$143,640	$143,640
Salvage Value	$91,277	$91,277	$91,277	$91,277	$91,277
Net Present Value	$943,391	$859,737	$781,349	$707,830	$638,817

[1] If the company were to sell all 400,000 units at $0.90 cents per unit over the course of each month. Total sales for each year= $360,000

4.2 Technical Evaluation of Extrusion Process

The previous section determined whether or not using the high moisture extrusion system to produce ready to eat oatmeal would be financially possible. Since the evaluation revealed that it would be economically feasible, a technical study was performed to determine the plausibility of actually implementing the system.

4.2.1 Preliminary Experiment

Product Evaluation

The finished product created using the extruder during the pilot study did not yield a finished product texture that was similar to the kettle batch, commercially made product. One major difference in the two formulations is that the control product includes functional ingredients such as acacia gum, whereas the extruded product did not. The pilot study did not include these ingredients into the formula in an effort to determine of rolled oats alone could be transformed by extrusion into an acceptable oatmeal texture. This in turn would reduce the total cost of raw materials. The trial yielding the most comparable results to the control was the third permutation, with a back extrusion force of 42. 22 N. Through visual analysis, it was observed that the product did not seem fully cooked as some of the oat groats were similar in appearance to the raw feed. Upon tasting the product, it was easily distinguished that starch gelatinization did not occur in many granules. The product had a chewy texture and explains why the back extrusions force was dissimilar from the control.

Table 4.4 Pilot Study Back Extrusion Results

Trial	Total Back Extrusion Force @ 30 secs. (N)	Coefficient of Variation (%)
1	48.9087 ± 6.9755	14.26
2	51.3423 ± 6.0123	11.71
3	42.2272 ± 7.3678	17.44
4	43.5958 ± 11.1268	25.52
Control	11.6979 ± 4.9470	42.29[1]

[1] Large outlier caused this number to be extremely high. In removing the outlier, the CV drops to 29%

One observation noted during back extrusion testing was that as the reaction zone temperature increased, the back extrusion force seemed to decrease. As the water rate increased, the back extrusion force also decreased. This aligned with our expectations that starch gelatinization would occur as a function of these two factors.

One can easily see that compression force was lower for the trials 3 and 4. Therefore, in the main experiment, it would be ideal to use a high water rate and explore using reaction zone temperatures that are higher than the profile seen in trials 3 and 4. Also, since the finished product texture was not comparable to that of the control in this experiment, it was concluded that incorporating the effect of a third factor, feed rate, into the main experiment might yield more promising results. The decision to include feed rate into the next experiment was based on the need to determine its relationship with water rate and reaction zone temperature, since starch gelatinization depends on the proportion of heat and water to the amount of starch.

4.2.2 Experiment 1

Product Evaluation

The experiment largely confirmed the original hypothesis that a lower dry feed rate and a higher water injection rate would be most comparable in texture with the kettle batch control product. The treatments which revealed the lowest force required to back extrude were LML, LHL and HHL permutations, at 40.01 N, 41.65 N and 47.57 N respectively. The coefficient of variation (CV) was considerably high in many of the trials. It is likely that this can be attributed human error during sample preparation for the texture analysis. It could also be partially attributed to the extrusion adjustment bias mentioned previously.

Table 4.5 Experiment 1 Back Extrusion Test Results

Trial Permutation	**Total Back Extrusion Force @ 30 secs. (N)**	**CV (%)**	**Trial Permutation**	**Total Back Extrusion Force @ 30 secs. (N)**	**CV (%)**	**Trial Permutation**	**Total Back Extrusion Force @ 30 secs. (N)**	**CV (%)**
LLL	53.2858 ± 16.0507	30.12	MLL	127.2318 ± 30.0309	23.60	HLL	93.9638 ± 5.8849	6.26
LLM	83.7552 ± 29.6810	35.43	MLM	137.2632 ± 22.0079	16.03	HLM	113.2838 ± 26.0382	22.98
LLH	245.972 ± 106.7730	43.41	MLH	248.9690 ± 22.2248	8.93	HLH	297.2764 ± 46.7144	15.71
LML	40.0122 ± 11.5525	28.88	MML	62.1542 ± 9.2206	14.83	HML	68.4932 ± 10.9976	16.05
LMM	102.5906 ± 30.8183	30.04	MMM	159.0234 ± 28.8945	18.17	HMM	109.5234 ± 25.5421	23.32
LMH	249.0834 ± 88.0454	35.35	MMH	239.0088 ± 28.8166	12.06	HMH	171.6976 ± 55.9866	32.61
LHL	41.6496 ± 20.7870	49.90	MHL	53.2360 ± 9.1083	17.10	HHL	47.5672 ± 11.1506	23.44
LHM	81.8836± 15.2887	18.67	MHM	97.2760 ± 9.3033	9.56	HHM	81.9102 ± 19.6487	23.99
LHH	61.3818 ± 8.3966	13.68	MHH	148.1070 ± 41.2098	27.82	HHH	93.8878 ± 10.0659	10.72

Reaction Zone Temperature

Adjusting the barrel temperature profile did not seem to have a positive effect on finished product quality or processing efficiency. When the reaction zone temperatures were at 60 and 70°C, the starch did not seem to be fully gelatinized and the oats were undercooked. Ratnayake and Jackson (2008) reported oat starch gelatinization temperatures between 60 and 70°C. It is likely that gelatinization did not occur because there was not enough dwell time in the barrel of the extruder to reach the onset, peak, or concluding temperatures required for oat starch gelatinization. When the reaction zone temperature was on the higher end, between 100 and 110°C, injected water transformed from liquid form to water vapor. The steam pressure caused the extruder to clog in the earlier feeding zones, which affected the flow rate of the product. These clogs were cleared by ramping down the feed rate in the extruder and then increasing the water rate to fully clear out any clogs. Once clogged product was removed, testing would resume after steady state had once again been reached.

Water Rate

The rate of water directly injected into the barrel definitely seemed to highly impact the product texture. When the feed rate was low and more water was injected into the barrel during processing, it led to a more consistent flow of product. This lower viscosity product decreased the total amount of force required to back extrude (Table 4.5). Subjectively, it was observed that when the water level was too low, there was not enough moisture in the environment to allow for starch gelatinization. The result was a thick, clumpy product in which particles were not evenly cooked due to the lack of sufficient water levels inside the barrel of the extruder. Oat starch requires excess water to fully gelatinize, but in this case there was a higher proportion of oats to water.

Feed Rate

The product texture appeared to be negatively impacted when the feed rate was at a high level. When feed rate was high (between 8 and 10 kg/hr), the product texture did not reach ideal consistency regardless of reaction zone temperature or water addition rate. However, it was observed that when the feed rate was set at 6 kg per hour, results that were more comparable to the control product were achieved. Since flow consistency was still an issue and the product texture results were extremely different to the control, it was determined that future feasibility studies should include testing the effect of factors that had been constant in the preliminary and main experiments.

4.2.3 Experiment 2

Product Evaluation

One limitation observed in regards to screw speed adjustments was that when running at higher water rates, the extruder could not be operated at screw speed values lower than 450 RPM. This was due to the fact that when using higher water injection rates, the rate of water going into the extruder was too high for the lower screw speeds to keep up with. Therefore if the screw speed was lowered, the water would begin to outflow at the feeding port and cause a system plug. It was determined that values of 450 RPM and higher could manage to extrude product successfully at water rates between 8 and 14 kg/hour.

It was expected that as the screw speed increased, the overall amount of shear force being applied to the product within the extruder would increase as well. This in turn would cause more aggressive mixing, making up for the fact that the product had a lower dwell time in the extruder barrel. However this was not the case in Experiment 2 as shown in Table 4.6 below.

Table 4.6 Experiment 2 Back Extrusion Results

Trial	**Total Back Extrusion Force @ 30 secs. (N)**	**Trial**	**Total Back Extrusion Force @ 30 secs. (N)**
1	47.0712 ± 4.4498	6	61.1492 ± 6.1624
2	58.6366 ± 8.8448	7	60.4844 ± 12.2516
3	60.0474 ± 4.2860	8	54.9110 ± 5.9843
4	65.5366 ± 12.4439	9	61.5684 ± 4.0742
5	61.7262 ± 7.0779	10	51.175 ± 2.4292

Screw Speed

The best back extrusion results actually occurred in the first treatment, with a screw speed of 450 RPM. This is the same speed that was used in the prior experiments. Since increasing the screw speed did not seem to have an effect on the response and the 450 setting had the best results, it was determined that this setting would likely yield outcomes closer to the control in future testing

4.2.4 Experiment 3

Product Evaluation

One observation made in Experiment 1 was that as the temperature in the reaction zone reach levels above 100°C, water in the surrounding zones turned to steam. This then created a plug in the feeding zone, as the product is not intended to be wet prior to entering the barrel. In an effort to remedy this, Experiment 3 was designed to have the barrel water entry point towards the center of the barrel as opposed to zone 2, which was directly adjacent to the feeding zone. This would allow more opportunity for the steam to condense back into liquid form prior to reaching the feeding area. If this could be achieved, then the temperature could be increased, allowing for a more efficient cook and potentially a more complete starch gelatinization. The prediction was that the extrudate oats would transform from an uncooked, elastic finished texture to an inelastic, gelatinized texture.

Water Injection Location

The results shown in Table 4.7 seemed to indicate that the trial which was most comparable to the control product was Trial C with a back extrusion force of 42.36 N. While port location 4 showed promising results in Trial C, the consistency of the product fluctuated greatly. This was mainly due to an increase in the steam plugging issue mentioned previously. Since the highest barrel temperatures occurred in the reaction zone, injecting water into those areas caused the phase change to happen in the water more rapidly than before. Because the oats being conveyed in the previous zone were not suspended, steam found a way to more quickly transfer into the feeding area. This caused plugging to occur frequently in the feeding zone. Therefore, it was determined that injecting water into zones which were close to the higher temperatures was not feasible.

Table 4.7 Experiment 3 Back Extrusion Results

Trial	Total Back Extrusion Force @ 30 secs. (N)
A	72.8118 ± 10.7449
B	54.1566 ± 4.8467
C	42.3584 ± 4.7183
D	54.3528 ± 8.1637
E	67.9324 ± 3.5748

4.2.5 Experiment 4

Product Evaluation

The control product made using the batch method contained sugar, salt, and gum. In Experiments 1, 2, and 3, these ingredients had not been used in an effort to keep material costs low. However, since none of these experiments were successful, it was determined that feed composition effect on high moisture extrusion of oatmeal should be explored. It was hypothesized that using high water rates in combination with the addition of the sugar, salt, and gum would decrease the amount of force required to back extrude the product. This stems from the various functional properties each of these ingredients supplies to the food matrix. It was important to use water rate injection level as a variable in this experiment due to the fact that the level of hydration of the gum in the product may impact the finished product texture as well. Table 4.8 displays the texture results from Experiment 4. The results are much lower than seen in previous experiments, which aligns with the aforementioned hypothesis.

Table 4.8 Experiment 4 Back Extrusion Results

Trial	Total Back Extrusion Force @ 30 secs. (N)
A	6.9770 ± 0.2294
B	18.8558 ± 4.1160
C	26.6876 ± 3.3285
A2	22.5296 ± 3.4490

Oatmeal Formula Effect

When visually comparing the product in Experiment 4 with previous Experiments, there was a clear difference in product texture and consistency. While the back extrusion force seems to be significantly lower based on the use of the new formula, one observation made throughout the experiment was that the mixture of ingredients did not evenly feed into the barrel of the extruder. The gum, sugar, and salt often sifted to the bottom of the feed hopper as product was being agitated and forced out through the auger. During certain periods of the experiment, the feed going into the extruder was highly inconsistent. At certain points, there was a very low proportion of oats to other ingredients and vice versa. Steady state of extrusion was never truly reached. This caused the extruder to yield product with highly variable back extrusion results regardless of water rate adjustment. The inconsistency also had an effect on the overall efficiency of the process, as the proportion of visually desirable product was very low.

Water Rate Effect

The treatment in trial A resulted a response that was significantly close to the control product, this response is deceiving since trial A2 utilized the exact same processing parameters as trial A and failed to yield similar results (Table 4.8). This is likely due to the inconsistency of proportional ingredients being fed into the barrel. For samples having fewer oats, more of the granular ingredients, and higher rate of water injection, the back extrusion force was low. It was observed that as the amount of oat proportion increased, so did the response. This is logical due to the fact that hydrated, cooked oatmeal with a high composition of the chosen functional ingredients with small particle size would not provide much resistance during back extrusion.

Since the particle size of the oats seemed to limit the efficacy of the high moisture extrusion system, it was determined that the next experiment should include reducing the particle size of the oats themselves, which had yet to be attempted.

4.2.6 Experiment 5

Product Evaluation

Since processing the oats to have smaller particle size had not been yet attempted, it was important to determine how this new raw material would react using high moisture extrusion. If the oats could be utilized without the functional ingredients, the cost savings would occur in formulation. However, reducing the particle size of the oats did not have a substantial impact on the texture of the finished product. The back extrusion results reflect similar results to previous experiments where oats were used as the only feed component. One main observation which was made during the experiment was the undesirable appearance of the finished product, which looked more like porridge than oatmeal.

Particle Size Reduction

It was predicted that reducing the particle size of the oat may allow for a more thorough cook. This stems from the assumption that creating more surface area would expose starch molecules to heat and water in a more efficient manner. Experiment 5 results reflected that this assumption was not practical, as the back extrusion force averaged 44 N (Table 4.9).

Table 4.9 Experiment 5 Back Extrusion Results

Trial	Total Back Extrusion Force @ 30 secs. (N)
A	43.8894 ± 3.3023
B	45.4104 ± 4.2070

Screw Speed Adjustment

Increasing the screw speed lowers the total dwell time for feed to be mixed with water and exposure to heat. Since the oat particles were going to be much smaller, it was predicted that the starch would not need as much time to hydrate and cook. Therefore, multiple screw speeds were used in an attempt to verify this concept. However, increasing the screw speed by did not yield a considerably different response in this experiment, meaning that decreasing dwell time by roughly 20% did not appear to have any effect on the finished product.

Although the regular blended oats did not yield results similar to the commercial product, it was thought that once they were mixed with the functional ingredients of the oatmeal formula used in Experiment 4 the back extrusion results might improve. In the next experiment, this hypothesis was tested.

4.2.7 Experiment 6

In all previous Experiments, one major limitation was the capacity of the Clextral water pump, which could only deliver water at a maximum rate of 8 kg/hr. Once this was realized, a higher capacity water pump was ordered, and the water rate maximum load was increased to 26 kg per hour. Throughout the main experiment and all previous feasibility studies, it was observed that the extrusion parameters which yielded that most desirable product were:

1) High water rates
2) Low feed rates
3) Low screw speed

4) Blended/reduced particle size oats (based on more consistent feeding)

5) Oats mixed with sugar, salt, and gum

In Experiment 6, these extrusion parameters were used in combination with an increased water addition rate through the use of the Novatech metering pump.

Product Evaluation

The increased capacity of the water pump allowed the product to achieve a texture which was very similar to that of the control product. (Table 4.10) One major issue with the product was the overall appearance of the product. As seen in Experiment 5, the product appearance was not desirable in that oat flakes had been reduced to a point in which it longer resembled typical oatmeal after being fully extruded. This is partially due to the fact that the auger inside the hopper of the extruder does apply some shear force to the feed as it is being conveyed into the barrel, reducing particle size subsequently. While the back extrusion results are very similar to that of the control, the appearance of the product was not. After reviewing the Experiment 6 product with manufacturers of frozen oatmeal, it was determined that the appearance of the product would hinder overall consumer acceptability.

Table 4.10 Experiment 6 Results and Observations

Trial	Total Back Extrusion Force @ 30 secs. (N)
A	18.6646 ± 1.0653
B	9.9238 ± 1.1871
C	15.8212 ± 0.8101

Increased Water Injection Capacity

It was observed that increasing the rate of water injection into the extruder to higher levels did not fully resolve the texture issues in previous experiments. While at certain points during processing product exiting the extruder appeared desirable, steady state was never fully achieved. This appeared to be due to the large difference in the amount of feed entering the barrel versus the amount of water. High water injection rates actually seemed to affect flowability of the feed and water mixture inside the barrel. Because the water entered the barrel at a much faster rate than the feed it is likely that the junction of feed and water in zone 2 became congested in certain periods throughout the run. This would then lead to product exiting the extruder that was high in water content but extremely low in feed content, and then at other sampling periods there would be more feed and less water.

Another limitation was the particle size of the oats. In order to make the product similar to the appearance of typical oatmeal, the particle size of the oats would need to increase. Upon attempting this in further experiments, it was realized that the large size of the oats in conjunction with the high water injection rate would at times cause product to clog in the mixing zones of the extruder. As mentioned previously, certain periods would have very little water flowing through the barrel, at high amounts of oat mix. When this oat mix reached the kneading screw profile elements in the mixing zone, it would at times obstruct the flowability of the product inside the barrel. This hence created a very inconsistent finished product texture with variable feed and moisture content.

CHAPTER 5

Conclusions

The high moisture extrusion system was evaluated to have a process cost which allowed for product pricing to be comparable to that of other frozen convenience products. While the capital investment would initially be substantial, the net present value for the technology could be reasonably high, depending on the size of the company. Overall, if it was technically possible for high moisture extrusion to be used to produce ready to eat oatmeal, it could have been recommended for usage.

It was determined that barrel temperature profile, water injection rate, raw material feed rate, screw speed, and the physical configuration of the raw materials are all associated with influencing the finished product texture of the extrusion process. The reaction zone temperature and water injection rate seemed to have the largest impact on the capability of the twin screw extruder to produce the high moisture ready to eat oatmeal. Another factor of importance was using a blend of rolled oats with sugar, salt, and acacia gum to increase the stability of the starch gel and enhance flavor and appearance. This was only possible while ensuring that the feeding rate of the dry blend was uniform through reducing the particle size of the oats. Technical hurdles such as low dwell times, steam plugging, and inconsistent feeding prevented complete starch gelatinization and the steady state of extrusion. Table 5.1 depicts key observations made throughout all experimentation, the technical explanation for those observations, and what recommendations could be made to improve the issue in the future. Based off of the extruder configuration and processing parameters used in this study, high moisture extrusion technology cannot be recommended for use to make ready to eat oatmeal.

Table 5.1 Conclusive observations made during oatmeal study

Key Observation	Technical Explanation	Future Recommendations
Back extrusion analysis was not reflective of starch gelatinization	Using the compression test to back extrude was intended to be an indirect method of measuring the degree of starch gelatinization. Various components such as beta glucan, sugar, salt, and gum competed in water interactions with starch. Therefore, any increase in viscosity could have been a result of these non-starch components thickening the mixture.	Use of differential scanning calorimetry or alternative direct starch gelatinization measurement would be ideal to determine the effect of extrusion processing on starch gelatinization in high moisture products.
Direct injection of water into the barrel of the extruder not effective for starch gelatinization	Obtaining the proper water: starch ratio required injecting high levels of water into the extruder. This led to steam plugging of the barrel due to the phase change of liquid to water vapor which contaminated the feeding zone.	Pre-blending and pre-hydrating the oat mixture would allow more time for the starch to fully hydrate. Experimentation could be performed to see how much soaking time is required to achieve starch gelatinization after heating and mixing occurs inside the barrel of the extruder.
Reaction zone temperature is not indicative of product temperature	There is a difference in temperature between control panel set points and the actual product temperature. Temperature is measured be the extruder using a probe located on the barrel itself. Heat must penetrate from the heating elements through the barrel and into the product itself. During physical changes such as starch gelatinization, temperature is a key component for completion. Therefore truly being able to monitor the product temperature, not just the temperature of the surface of the barrel, is important.	Temperature probes are available which can gather real time temperature readings from the product inside the extruder. In future experiments, these should be used so that one can be sure that onset, peak, and conclusion gelatinization temperatures were reached inside the product.

Table 5.1 (Cont'd) Conclusive observations made during oatmeal study

Reducing the particle size of whole rolled oats caused finished product to be visually unacceptable	In order for the feed material to be distributed evenly into the feeding zone, particle size must be similar. Denser, granular particles such as sugar, salt, etc. will gravity feed towards the bottoms of the hopper much more quickly than lower density materials such as oats. However, reducing the particle size of the oats creates a finished product that no longer resembles oatmeal. It has an extremely homogeneous texture, similar to cream of wheat.	Utilizing the pre-hydration method of oatmeal dry blend preparation and then force feeding the material into the feeding zone would allow for a difference in particle size and a finished product which has partial oat particles visible to the naked eye therefore resonating with consumers as oatmeal.
Dwell time in the extruder was too low to achieve starch gelatinization	In order for the starch to fully hydrate and gelatinize, more dwell time is required inside the barrel. This is not possible with screw speeds less than 450 RPM due to water back flowing into the feeding zone causing system plugs.	When utilizing the pre-hydration method of high moisture extrusion of oatmeal, screw speeds should be set between 100 and 300 RPM in order to allow for enough cooking time

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APPENDICES

Appendix A

Glossary of Terms

1) M.C. – Moisture Content
2) Feed- The raw material to be extruded
3) Extrudate- Finished product which has been extruded
4) Back Extrusion- The process of forcing material opposite of the direction in which the plunger is moving via the small gap between the plunger and cell wall
5) RPM – Revolutions per minute
6) Kg/hr – kilograms per hour