ACHARYA N. G. RANGA AGRICULTURAL UNIVERSITY

B. Tech (Food Technology)

Course No.: FDST 316

Credit Hours: 2 (1+1)

THEORY STUDY MATERIAL

EXTRUSION TECHNOLOGY

Prepared by

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Lecture outlines:

1**. Course No. : FDST - 316**
2. **Title: Extrusion Technology**
3. Credit hours: 2 (1+1)
4**. General Objective**: To impart knowledge to the students about extrusion technology, principle of working, classification of extruders according to process and construction, extruded products and their processing.
5. **Specific Objectives**
a) Theory
By the end of the course, the students will be able to
i. learn about use of extrusion technology in food industry
ii. study about Extrusion cooking, preconditioning of raw material, types of extruders and operating parameters
b) Practical
By the end of the course, the students will be able to
i. learn about preparation of breakfast cereals and snack foods using extruder
ii. Study processing parameters of extruders for preparing different food products
iii. Prepare extruded products, snack foods and Texturized Vegetable Protein by extruder

A) Theory Lecture Outlines

1. Extrusion: definition, introduction to extruders and their principles, types of extruders
2. Extruders in the food industry: History and uses of extruders in the food industry
3. Single screw extruder: principle of working, net flow, factors affecting extrusion process,
co-kneaders
4. Twin screw extruder: counter rotating and co-rotating twin screw extruder
5. Process characteristics of the twin screw extruder : feeding, screw design, screw speed, screw configurations, die design
6. Twin screw extruder: Barrel temperature and heat transfer, adiabatic operation, heat transfer operations and energy balances
7. Problems associated with twin screw extruder
8. Pre-conditioning of raw materials used in extrusion process, Pre-conditioning operations
and benefits of pre-conditioning and devolatilization
9. Interpreted-flight expanders - extruders, dry extruders
10. Chemical and nutritional changes in food during extrusion

11. Practical considerations in extrusion processing: pre-extrusion processes, cooker extruder Profiling
12. Practical considerations in extrusion processing: Addition and substraction of materials, shaping and forming at the die, post extrusion processes
13. Break fast cereals: introduction, type of cooking - High shear cooking process, steam cookers, low shear, low pressure cookers and continuous staem pre-cooking, available brands
14. Break fast cereal processes: traditional and extrusion methods, classification of break fast cereals - flaked cereals, oven puffed cereals, gun puffed cereals, shredded products
15. Texturized vegetable protein: Definition, processing techniques, and foods
16. Snack food extrusion: Direct expanded (DX) and third generation (3G) Snacks: types, available brands, co- extruded snacks and indirect-expanded products

B) Practical Class Outlines

1. Study of different extruders
2. Pre-processing methods for extrusion cooking - I
3. Pre-processing methods for extrusion cooking - II
4. Pre-processing methods for extrusion cooking -III
5. Processing Texturized protein products
6. Processing of Cereal based and Break fast cereal products - I
7. Processing of Cereal based and Break fast cereal products - II
8. Processing of Snack items
9. Processing of Snack items
10. Processing of vegetable based extruded products - I
11. Processing of vegetable based extruded products - II
12. Processing of vegetable based extruded products - III
13. Study of factors affecting extrusion cooking – moisture content, Diameter, temperature, pressure, screw speed, time

14. Study of factors affecting extrusion cooking – moisture content, diameter, temperature, pressure, screw speed, time
15. Study of factors affecting extrusion cooking – moisture content, diameter, temperature,

pressure, screw speed, time
16. Quality evaluation of extruded products

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York.

LECTURE: 1

Extrusion: definition, introduction to extruders and their principles, types of extruders

Def**inition**: Extrusion is a process which combines several unit operations including mixing, cooking,
kneading, shearing, shaping and forming.

Introduction:

1. Extrusion technologies have an important role in the food industry as efficient manufacturing processes. Their main role was developed for conveying and shaping fluid forms of processed raw materials, such as doughs and pastes.
2. Extrusion cooking technologies are used for cereal and protein processing in the food and, closely related, pet foods and feeds sectors. The processing units have evolved from simple conveying devices to become very sophisticated in the last decade.
3. Today, their processing functions may include conveying, mixing, shearing, separation, heating or cooling, shaping, co-extrusion, venting volatiles and moisture, flavour generation, encapsulation and sterilization.
4. They can be used for processing at relatively low temperatures, as with pasta and half product pellet doughs, or at very high ones with flatbreads and extruded snacks. The pressures used in extruders to control shaping, to keep water in a superheated liquid state and to increase shearing forces in certain screw types, may vary from around 15 to over 200 atmospheres.

Extrusion cooking has gained in *popularity* over the last two decades for a number of reasons:

• Versatility: a wide range of products, many of which cannot be produced easily by any other process, is possible by changing the ingredients, extruder operating conditions and dies

• Cost: extrusion has lower processing costs and higher productivity than other cooking and forming processes

• Productivity: extruders can operate continuously with high throughput

• Product quality: extrusion cooking involves high temperatures applied for a short time, retaining many heat sensitive components of a food
• Environmentally-friendly: as a low-moisture process, extrusion cooking does not produce significant process effluents, reducing water treatment costs and levels of environmental pollution.

Principle: The principles of operation are similar in all types: raw materials are fed into the extruder barrel and the screw(s) then convey the food along it. Further down the barrel, smaller flights restrict the volume and increase the resistance to movement of the food. As a result, it fills the barrel and the spaces between the screw flights and becomes compressed.

As it moves further along the barrel, the screw kneads the material into a semi-solid, plasticized mass. If the food is heated above 100ºC the process is known as *extrusion cooking* (or *hot extrusion*). Here, frictional heat and any additional heating that is used cause the temperature to rise rapidly. The food is then passed to the section of the barrel having the smallest flights, where pressure and shearing is further increased.

Finally, it is forced through one or more restricted openings (dies) at the discharge end of the barrel as the food emerges under pressure from the die, it expands to the final shape and cools rapidly as moisture is flashed off as steam. A variety of shapes, including rods, spheres, doughnuts, tubes, strips, squirls or shells can be formed. Typical products include a wide variety of low density, expanded snack foods and ready-to-eat (RTE) puffed cereals.

Cold extrusion, in which the temperature of the food remains at ambient is used to mix and shape foods such as pasta and meat products. Low pressure extrusion, at temperatures below 100ºC, is used to produce, for example, liquorice, fish pastes, surimi and pet foods.

Extrusion cooking is a high-temperature short-time (HTST) process which reduces microbial contamination and inactivates enzymes. The main method of preservation of both hot- and cold-extruded foods is by the low water activity of the product (0.1–0.4), and for semi-moist products in particular, by the packaging materials that are used.

Table 1: Examples of extruded foods

Types of product	Examples

Cereal-based products	Expanded snackfoods RTE and puffed breakfast cereals Soup and beverage bases, instant drinks Weaning foods Pre-gelatinised and modified starches, dextrins Crispbread and croutons Pasta products Pre-cooked composite flours
Sugar-based products	Chewing gum Liquorice Toffee, caramel, peanut brittle Fruit gums
Protein-based products	Texturised vegetable protein (TVP) Semi-moist and expanded petfoods and animal feeds and protein supplements Sausage products, frankfurters, hot dogs Surimi Caseinates Processed cheese

Food extruders can perform one or several functions at the same time while processing food or feed:

Including mixing/degassing ingredients, homogenization, grinding, shearing, starch cooking (gelatinization), protein denaturation and texturization, texture alteration, enzyme in-activation, pasteurization and sterilization of food spoilage and pathogenic microorganisms, thermal cooking, shaping products, expansion, puffing, agglomerating ingredients, dehydration, unitizing etcetera.

History:

At first, in 1935, the application of single-screw extruders for plasticating thermo-plastic materials became more common as a competitor to hot rolling and shaping in hydraulic-press equipment. A plasticating single-screw extruder is provided with a typical metering screw, developed for this application .

In the mid-1930s we notice the first development of twin-screw extruders, both co-rotating and counter-rotating, for food products. Shortly after, single-screw extruders came into common use in the pasta industry for the production of spaghetti and macaroni-type products. In analogy with the chemical polymer industry, the single-screw equipment was used here primarily as a friction pump, acting more or less as continuously cold forming equipment, using conveying-type screws. It is remarkable that nowadays the common pasta products are still manufactured with the same single-screw extruder equipment with a length over diameter ratio (L/D) of approximately 6–7. However, there has been much development work on screw and die design and much effort has been put into process control, such as sophisticated temperature control for screw and barrel sections, die tempering. and the application of vacuum at the feed port. Finally, the equipment has been scaled up from a poor hundred kilos hourly production to several tons [1, 2].

The development of many different technologies seems to have been catalyzed by World War II, as was that of extrusion-cooking technology. In 1946 in the US the development of the single-screw extruder to cook and expand corn- and rice-snacks occurred. In combination with an attractive flavoring this product type is still popular, and the method of producing snacks with single-screw extruder equipment is common now.

Lecture: 2

Extruders in the food industry: History and uses of extruders in the food industry.

CLASSIFICATION OF EXTRUDERS:

- Extruders are classified into two types according to operation: Hot and cold extruders
- Based on type of construction extruders are classified into: Single screw and twin screw extruder

Types of extruders and their history:

Segmented screw/barrel single-screw 'wet' extruders

A typical single-screw extruder consists of a live bin, feeding screw, preconditioning cylinder, extruder barrel, die and knife. The live bin provides a buffer of raw material so the extruder can operate without interruption. Typically, the height of raw material in the bin is maintained within defined limits by high and low sensors which activate a conveyor supplying the bin. The bin is designed to prevent bridging of its contents and blocking the feed screw leading to the pre conditioner. Speed of the feed screw to the conditioner or extruder must be variable to ensure a continuous uniform supply of raw material, which, in turn, leads to consistent and uniform operation of the extruder.

Because single-screw extruders have relatively poor mixing ability, they are usually supplied with premixed material which often has been preconditioned\ with added steam and water. Generally, preconditioning prior to extrusion enhances extrusion processes which benefit from higher moisture content and longer equilibration time. Preconditioning of the raw material typically improves the life of wearing components in the extruder by several folds. Although the weight of ingredients in the extrusion system is increased, preconditioners are relatively inexpensive to build for the volume they hold and time added to the process for preconditioning. Product quality can be improved greatly by preconditioning the raw ingredients.

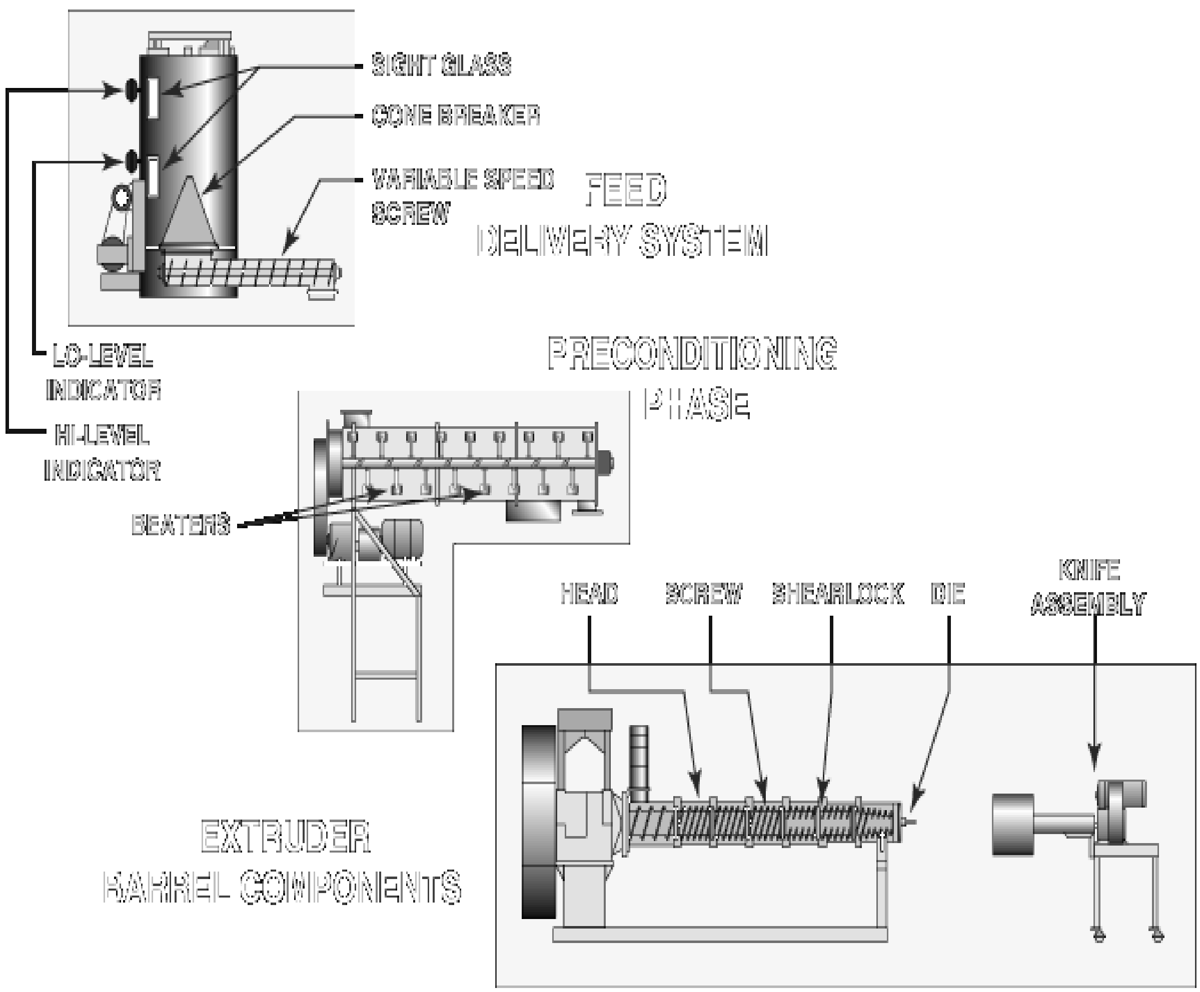

FIG: 1 Single screw wet extruder

Application

The first major commercial application of the single-screw extruder in the food processing industry was conversion of semolina flour into pasta using solid screws. This low-shear, low-temperature-forming process first found commercial production in the 1920s and 1930s, and remains a standard process although equipment has improved (Huber, 2000). Several new developments in the single-screw extruder have further increased its efficiency and versatility. A brief list of the products made by single-screw extruders includes:

- direct expanded corn snacks
- texturized vegetable protein
- ready-to-eat breakfast cereal
- production of full fat soy
- pet foods
- floating and sinking aquatic feed
- production of baby foods
- rice bran stabilization
- precooked or thermally modified starches, flours and grain
- breading.

Twin-screw extruder

Recent year s have seen increasing requirements for new products with intricate shape s and small sizes that are beyond the capabilities of single-screw systems. Twin-screw extruders can fill some of these needs. The term ‘twin-screw’ applies to extruder s with two screws of equal length placed inside the same barrel. Twin-s crew extruder s are more complicated than single screw extruders, but at the same time provide much more flexibility and better control. Twin screw extruders are generally categorized according to the direction of screw rotation and to the degree to which the screws intermesh:

1 . Counter- rotating twin- screw extruder s
2 . Co-rotating twin-screw extruder s.

In the counter-rotating position the extruder screw rotates in the opposite direction, whereas in the co-rotating position the screw rotates in the same direction. These two categories can be further subdivided on the basis of position of the screw in relation to one another into: intermeshing and non int
ermeshing.

The non-intermeshing twin-screw extruder is like two single-screw extruders sitting side by side with only a small port ion of the barrels in common. These types of extruder s depend on friction for extrusion, just like single screw extruders. In non-intermeshed extruders, neither pumping nor mixing is
positive. Their design does not provide a positive displacement action for pumping the product forward.

In intermeshing twin screw extruders, the screws partially overlap each other in a figure ‘8’ barrel track, resulting in positive pumping, efficient mixing and self-wiping action (only in co-rotating machines; limited mixing in counter-rotating machines), differentiating these types of extruders from non-intermeshing and single-screw machines. These extruders are like a positive displacement pump, forcing material in the barrel between the screws to move toward the die by rotation of the screw.

Co-rotating self-wiping types of extruders are most commonly used in the food industry. These extruders significantly increased the variety of products that can be made using extrusion technology. The twin-screw extruder consists of several sub-components very similar to single-screw extruders (live bin, feeding screw, preconditioning cylinder, extruder barrel, jacketed heads and rotating screw). A detailed discussion of these components is presented in the single-screw extruder section. The bearing assembly in the twin-screw extruders is much more complicated because more components (such as drive and torque dividing gears) are required. Twin-screw extruders also have three processing zones, feeding, kneading and a final processing zone very similar to single-screw extruders. These zones are described in the single-screw extruder section.

Applications

Twin-screw extruders got their popularity in the food industry in the mid-1980s– mid-1990s. Originally developed for processing plastics, food companies began using twin-screw extruders for products like sticky caramels and candies that could not be made with single-screw machines. Very soon, twin-screw extruders become popular with the food manufacturers for specialized food items. Recent improvements in single-screw extruders have made it possible to process several foods formerly made on twin-screw extruders, possibly limiting the market for twin-screw extruders:

1) Variable speed drives (VFD) gave single-screw additional flexibility and are approaching twin-screw
2) Computer control systems
3) Improved gravimetric feed systems and mass flow meters for precise metering of ingredients/recipe components.
Presently, twin-screw extruders are being used for the following different food and feed items.
• co-extruded snacks and other food items
• food gums
• reformed fruit bits and sheets
• topping and bakery analogs
• precooked pasta
• noodles, spaghetti and macaroni
• imitation nuts
• third generation snacks
• bread-like products (crisp bread)
• pastry doug
• texturized vegetable protein (soy)
• wheat gluten textured products
• semi-moist food
• soup and gravy mixes
• sugar crust liqueurs
• pet treats
• three-dimensional snacks
• three-dimensional confections and toffees
• cheese and casein products
• beer powders
• meat analog
• texturized vegetable protein from partially defatted soy flour
• stabilization of rice bran
• multicolor food and snacks
• meat and power bars
• special energy bars with resin filling
• marshmallow products
• cereals and corn flakes
uniform size and shape s
• ultra-sm all produc t sizes (less than 1.5 mm)
• produc ts mad e with low densi ty powder
• special formulat ions.

Table: 1 Typical process parameters

Process	Temp. (ºC)	Max. pressure (bar)	Moisture (%)	Max. Fat (%)	Cook* (%)
Pellet press	60-100		12-18	12	15-30
Expander/ pellet press	90-130	35-40	12-18	12	20-55
Dry extrusion	110-140	40-65	12-18	12	60-90
Wet extrusion					
Single-screw Twin-screw	80-140	15-30	15-35	22	80-100
Twin screw	60-160	15-40	10-45	27	80-100

Lecture: 3

Single screw extruder: principle of working, net flow, factors affecting extrusion process,
Co -kneaders

Single-screw extruders

The equipment (Fig. 14.1) consists of a cylindrical screw that rotates in a grooved cylindrical barrel, made from hard alloys or hardened stainless steel to withstand the frictional wear. The length to diameter ratio of the barrel is between 2:1 and 25:1. The pitch and diameter of the screw, the number of flights and the clearance between the flights and the barrel can each be adjusted to change the performance of the extruder. The screw is driven by a variable speed electric motor that is sufficiently powerful to pump the food against the pressure generated in the barrel. The screw speed is one of the main factors that influence the performance of the extruder: it affects the residence time of the product, the amount of frictional heat generated, heat transfer rates and the shearing forces on the product. Typical screw speeds are 150–600 rpm, depending on the application. Compression is achieved in the extruder barrel by back pressure, created by the die and by:

- increasing the diameter of the screw and decreasing the screw pitch
- using a tapered barrel with a constant or decreasing screw pitch
- placing restrictions in the screw flights.

Die pressures vary from around 2000_103 Pa for low viscosity products to 17 000_103 Pa for expanded snackfoods. Single-screw extruders can be classified according to the extent of shearing action on the food into:

- *High shear*. High speeds and shallow flights create high pressures and temperatures that are needed to make breakfast cereals and expanded snackfoods.
- *Medium shear*. For breadings, texturised proteins and semi-moist petfoods.
- *Low shear*. Deep flights and low speeds create low pressures for forming pasta, meat products and gums. In extrusion cooking, much of the energy from the extruder motor is lost as friction and rapidly heats the food (between 50 and 100% of total energy input. Additional heating can be achieved using a steam-jacketed barrel and/or by a steam heated screw (in some applications the jacket is also used to cool the product using cold water). In other designs, electric induction heating elements are used to heat the barrel directly. Some products also require the extruder die to be heated to maintain the viscosity and degree of expansion, whereas others require the die to be cooled to reduce the amount of expansion.

Single-screw extruders have lower capital and operating costs and require less skill to operate and maintain than twin-screw machines do. They are used for straightforward cooking and forming applications, when the flexibility of a twin-screw machine is not needed.

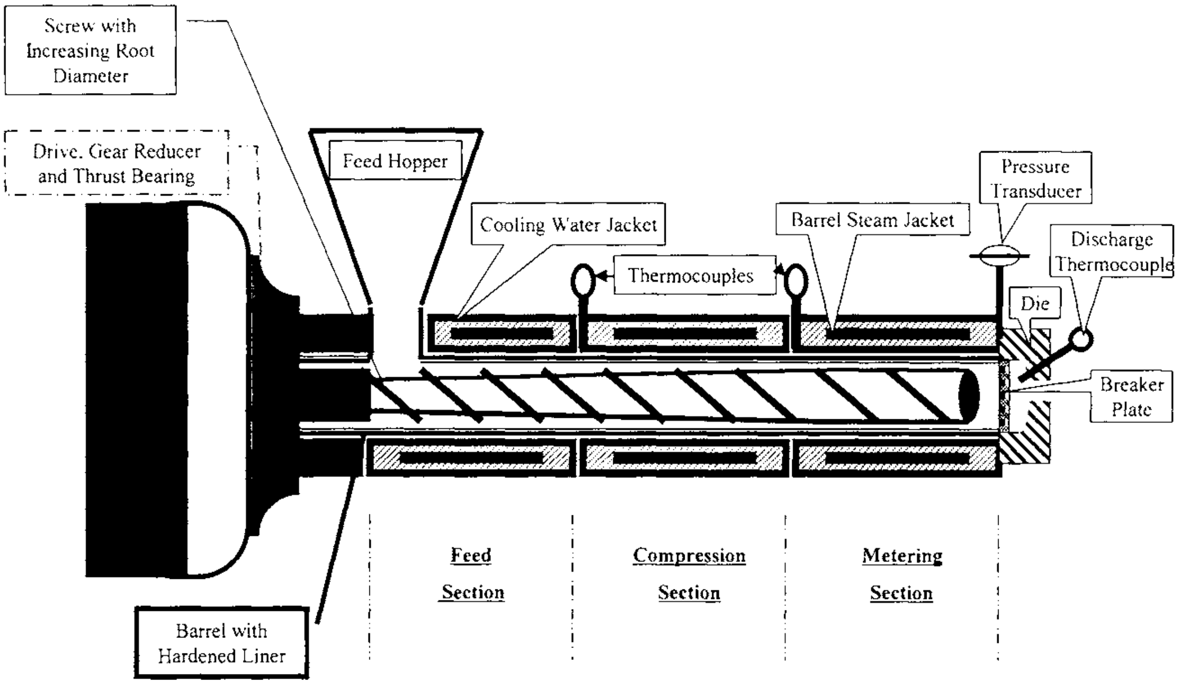

Figure 2 Single solid screw extruder—basic components.

Factors affecting extrusion cooking :

The two factors that most influence the nature of the extruded product are the rheological properties of the food and the operating conditions of the extruder.

Rheological properties of the food

The properties of the feed material have an important influence on the texture and colour of the product; the most important factors are:

1. the type of feed materials
2. their moisture content
3. the physical state of the materials
4. their chemical composition, particularly the amounts and types of starches, proteins, fats and sugars
5. the pH of the moistened material.

Operating characteristics

The most important operating parameters in an extruder are:

6. temperature
7. pressure
8. diameter of the die apertures
9. shear rate.

Co-kneaders:

Lecture: 4

Twin-screw extruder: counter rotating and co-rotating twin screw extruder:

Twin-screw extruders

The screws in twin-screw extruders rotate within a ‘figure of 8’ shaped bore in the barrel.

Screw length to diameter ratios are between 10:1 and 25:1 (Harper, 1987). Extruders are classified according to the direction of rotation and the way in which the screws intermesh. Co-rotating intermeshing screws, which are self-wiping (the flights of one screw sweep food from the adjacent screw) are most commonly found in food-processing applications (Fig. 14.4). The spacing between the flights can be adjusted so that large spaces initially convey the material to the cooking section and then smaller spaces compress the plasticized mass before extrusion through an inter-changeable die. One of the main advantages of twin-screw extruders is the greater flexibility of operation that is possible by changing the degree of intermeshing of the screws, the number of flights or the angle of pitch of the screw. 'Kneading discs' can also be fitted to the screws so that the product passes between and through the discs to increase the kneading action. Twin-screw extruders have the following advantages:

- The throughput is independent of feed rate, and fluctuations in production rate can be accommodated by the positive displacement action of the screws. In contrast, a single screw must be full of material to operate effectively. The positive displacement also produces higher rates of heat transfer and better control of heat transfer than a single screw does.
- Twin-screw machines handle oily, sticky or very wet materials, or other products that slip in a single screw. The limitations for single- and twin-screw machines are respectively 4% and 20% fat, 10% and 40% sugar, and 30% and 65% moisture. There is therefore greater flexibility in operation using different raw materials. Forward or reverse conveying is used to control the pressure in the barrel. For example, in the production of liquorice and fruit gums, the food is heated and compressed by forward conveying, the pressure is released by reverse conveying, to vent excess moisture or to add additional flavour ingredients, and the food is then recompressed for extrusion.
- A short discharge section develops the pressure required for extrusion and thus subjects a smaller part of the machine to wear than in single-screw extruders.
- A mixture of particle sizes, from fine powders to grains, may be used, whereas a single screw is limited to a specific range of granular particle sizes.

The main limitations of twin-screw extruders are the relatively high capital and maintenance costs (up to twice the cost of single-screw equipment) and the greater constraints on operating ranges. The complex gearbox that is needed to drive the twin screws results in limitations on the maximum torque, pressure and thrust that can be achieved.

Analysis of heat transfer inside a twin-screw extruder shows that the physical phenomena involve a number of parameters that must be controlled:

(a) Physical, thermal and rheological properties of foodstuffs

It is important to draw a distinction between the physical and thermal properties and the rheological properties. The physical properties are the moisture content and the specific gravity. The moisture content (MC expressed in %) determines the other properties of the material. One must differentiate between the moisture content in a dry base from the moisture content in a wet base. The former corresponds to the intrinsic quantity of water present in a raw material. The latter is the total quantity of
water after water has been added to the material. The specific gravity is used to calculate the volumetric flow and the degree of fill of the screws. The thermal properties are the specific heat, the melting point, the enthalpy of fusion and the thermal conductivity. The specific heat of the foodstuffs used in extrusion cooking varies from 1500 to 2500 J.kg_1.K_1 depending on the nature and state of the material. In the case of a mixture of various ingredients, it is determined using an additive rule that takes into account the percentage and specific heat of each ingredient. The thermal conductivity of foodstuffs lies between 0.1 and 0.5 W.m_1.K_1. The temperature and the enthalpy of fusion are necessary for calculating the energy that must be supplied to the material for it to undergo a change of phase. For maize starch, the change in the melting point as a function of the moisture content follows Flory's law.

The viscosity of the material is the rheological property governing the viscous dissipation generated by the shear stresses. Special instruments such as rheo meters are necessary to determine the viscosity.

(b) Convective heat transfer coefficient between material and barrel

The quality of the heat transfer in an extruder depends on the convective heat transfer coefficient between material and barrel. The power transferred is proportional to this coefficient. There has been no specific experimental research aimed at quantifying this coefficient. The conclusion is that transfer is
better first when the material is molten and, secondly, when a twin- screw extruder is used.

(c) Transfer area between material and barrel

The power transferred between the material and the barrel is proportional to the transfer area. In the case of a twin-screw extruder, this area is proportional to the degree of fill of the screws defined b y the operational conditions (rotation speed of the screws, pitch of the screws, material throughput, density of the material). The transfer area is the product of the internal surface area of the barrel and the degree of fill of the screws. The different expressions given in the literature are based upon the same structure. This is the ratio of the actual volume of material to the available volume.

(d) Viscous dissipation: shear rate – viscosity – volume

Viscous dissipation is responsible for the conversion and intimate mixing of the material in the extruder. This thermal power of mechanical origin is a significant factor in the thermal change s in the material. These are generated by a velocity gradient, known as the shear rate, within a volume of material.

(e) Difficulties in evaluating certain thermal parameters

This inventory of thermal parameters involved in extrusion cooking shows the limitations affecting their understanding and determination. The lack of knowledge of these parameters stems essentially from the difficulty of measuring them. The extreme conditions of temperature, shear, flow and pressure inside an extruder are difficult to reproduce using existing measurement facilities. If thermal calculations are to be valid, good estimates of all the parameters involved are necessary

Lecture 5:

Process characteristics of the twin screw extruder: feeding, screw design, screw speed, screw configurations, die design.

Lecture: 6

Twin screw extruder: Barrel temperature and heat transfer, adiabatic operation, heat transfer operations and energy balances

Lecture: 7

Problems associated with twin screw extruder

Lecture: 8

Pre-conditioning of raw materials used in extrusion process, Pre-conditioning operations and benefits of pre-conditioning and devolatilization

Lecture: 9

Interpreted-flight expanders - extruders, dry extruders

Interrupted flight extruders

The basic design for most of today's interrupted flight extruders (also called 'expanders') was developed and introduced in the United States by the Anderson International Company (Cleveland, Ohio) as the 'Anderson Grain Expander' in the latter 1950s for processing pet foods and other cereal products. Expanders were exported to Brazil for stabilizing rice bran in 1965, Ecuador in 1969, and Mexico in 1970. This design was applied to preparing soybeans and cotton seed for solvent extraction in Brazil in the early 1970s. Brazilian- made expanders were brought back to the United States for processing cottonseed in the late 1970s.

An estimated 70% of the domestic tonnage of soybeans and cottonseed processed in the United States is now prepared for solvent extraction by interrupted flight extruders. Currently, machines of similar design are made in the United States, Brazil, Indi a, Switzerland and Ger many. A typical interrupted flight expander extruder is shown in Fig. 3. An interrupted flight extruder is mechanically different from other extruders, because it was developed from a screw press. Screw presses and interrupted flight extruder s are similar in that a revolving interrupted flight pushes the material through a cylindrical barrel and out through an opening at the barrel's end. Rather than round 'shear bolts', the protrusions into the open area between flights are cal led 'breaker bars' in screw presses. However, a screw press is a more massive and costly machine; it generates more pres sure, and it is equipped with a barrel section that allows oil to flow away from the solids. Although extruders are often equipped with steam -heated /water-cooled jackets, commercial interrupted flight expanders usually are not jacketed and rely on direct steam injection for supplemental heat beyond that created by mechanical shear of the ingredients.

The expander's internal mechanism consists of a rapidly rotating worm shaft, having individual worms with an interrupted flight positioned inside a smooth walled barrel equipped with removable stationary pins protruding from the barrel and intermeshing with the interruptions of flight. The purpose of the intermingling of the rotating worms with stationary pins is to provide a high shear, turbulent mixing action, which kneads the solid formulation with the injected water and steam to provide rapid and uniform absorption of the injected moisture into all of the solid matter. As the steam is absorbed, it releases its heat of vaporization which elevates the temperature of the ingredients. Frictional heat is also generated by the rapid motion of the flights, further elevating the temperature as they compact and works the mixture subjecting it to increasingly higher pressures as it is forced through the length of the barrel. By the time the mixture reaches the end of the length of the barrel, it is thoroughly cooked and under high enough pressure and temperature (120–150ºC; 248–302ºF), resulting in much of the moisture flashing off as product exits the expander.

Applications

Anderson 6 and 8 inch diameter expanders played a lead role in processing pet foods until modern segmented single-screw extruders were developed. Expanders now play a major role in preparing oilseeds for solvent extraction, and special high shear heads have been developed for shearing oilseeds before screw pressing. Expanders are still used for making pet foods and floating aquatic feeds. Since expanders have less shearing action than dry extruders, soybeans should be ground before entering the machine when making full-fat soybean meal. As a result, less wear generally occurs in expanders than in dry segmented extruders, smaller electric motors can be used, and maintenance costs are lower. A short, interrupted flight shear bolt section is often included in large feed-type expanders, 12 inch diameters and up, used to precondition/precook feed formulas before pelleting. Applications of expanders include:

- full fat soybeans
- oilseeds preparation for solvent extraction
- oilseeds preparation for 'hard pressing' to 5–6% residual oil in the meal
- rice bran stabilization
- pet foods
- aquaculture feed
- feeds for other animals (pig, cattle, horse, mink)
- snack foods
- drying of synthetic rubber and plastic polymers.

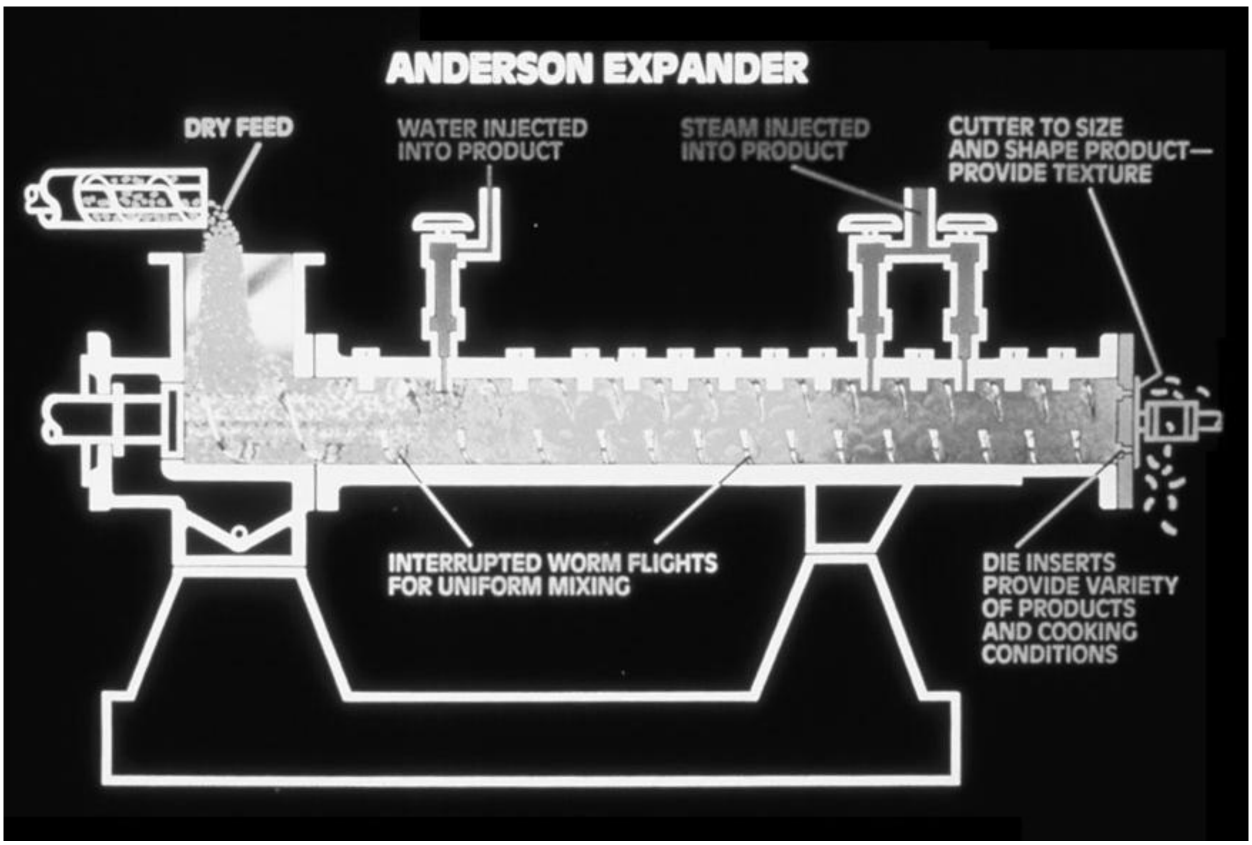

Fig. 3 Typical interrupted flight expander extruder

Dry extruders:

The term 'dry' extrusion means that this type of extruder does not require an external source of heat or steam for injection or jacket heating, and all product heating is accomplished by mechanical friction. This type of extruder was developed initially for processing whole soybeans on the farm. Dry extruders can process ingredients which have a wide range of moisture contents, i.e. 10–40%, depending on the premixed formula. If the ingredients have sufficiently low initial moisture content, drying of the product after extrusion cooking may not be necessary. Moisture loss in dry extrusion is in the form of steam flash-off at the die, and the extent depends on initial moisture in the ingredients and product exit temperature. Dry extruders have the option of water injection during extrusion. Usually starchy material requires some moisture in order to gelatinize. Considerable advances have been made in the design of dry extruders and their components. Recent research has shown that efficiency/throughput of the extruder is almost doubled if the starting material can be preconditioned with steam and water. Longer barrels will work much well in some applications than the shorter barrel formerly used for soybeans.

Dry extruders are single-screw extruders with screw segments and steam locks (choke plates) on the shaft for increasing shear and creating heat. When material moves through the barrel, and comes up against these restrictions, it is unable to pass through, pressure increases, and a back flow is created. Usually these restrictions are arranged in such a way that they increase in diameter toward the die end of the screw to create more pressure and shear as the product reaches the die. This build-up of pressure and temperature, together with the shear stresses developed, plasticizes the raw materials into viscous paste or puffed shapes, depending on the raw material. There is no basic difference between the above and the ‘wet’ extruders, except that more shear occurs in dry extruders to create heat.

In dry extrusion, pressure and temperature are at their maximum just before leaving the die. The die design and opening also play very important roles in pressure build-up. The cooking range in a dry extruder can be 82–160ºC (180–320ºF) with very high pressure. As soon as the material exits the extruder dies, pressure is instantaneously released from the products, causing the internal moisture to vaporize into steam and making the product expand and results in sterilization of the product.

Applications

Dry extruders can be used for food, feed and recycling of food and feed byproducts. A major use of the dry extruder is in preparing oilseeds for screw pressing of oil – primarily soybeans and cottonseed, although they have been applied to sunflower, peanut and canola seed processing. In the process, soybeans and cottonseed are extruded using a dry extruder, followed by pressing in a parallel bar screw press to remove the oil. Extrusion prior to screw pressing greatly increases throughput of the expeller over the rated capacity. Oil and meal produced by this method are remarkably stable because extrusion also releases natural antioxidants in oilseeds. This process is used around the world for processing raw soybeans into full fat soybeans and partially defatted soybean meal. Cereal grain fractions and other starchy raw materials can be preceded by dry extrusion. Applications include processing of:

- cereals and starches
- snack foods and break fast cereals
- textured vegetable protein
- enzyme inactivation in rice bran
- pet food
- aquaculture feed
- feed s for other animals (pig, cattle, horse , min k)
- recycling wet waste from food, and animal by –products

Lecture: 10

Chemical and nutritional changes in food during extrusion Extruders offer food scientists a palette of conditions and ingredients from which new foods may be created. Although snack foods were among the first commercially successful extruded foods, today extruders produce many foods of nutritional importance. Simple single- screw extruders are relatively inexpensive and easy to maintain, thus international research projects have focused on these machines as food processors for the needy. External energy supplies may not be necessary, as friction from the rotation of the screw may be sufficient to thoroughly cook the food. Processes can be developed to take advantage of donated foods such as dried milk as well as indigenous crops such as beans, millet, and cassava. Use of local crops may help improve sustainability of operations past immediate crises and reduce reliance on foreign aid. Extruded collets may be easily ground into flour that can be mixed with milk or water to form gruel for infants or weakened individuals.

Extrusion parameters affecting nutritional quality

Feed material composition
Prior processing history of feed materials
Water content
Material feed rate
Screw speed
Screw configuration
Barrel temperature
Injection
Die configuration

2 Macronutrients

Carbohydrates

Starchy tubers and grains provide important energy and satiation in most diets. Sugars provide sweetness and are involved in numerous chemical reactions during extrusion. Control of carbohydrates during extrusion is critical for product nutritional and sensory quality. Extrusion conditions and feed materials must be selected carefully to produce desired results. For example, a weaning food should be highly digestible, yet a snack for obese adults should contain little digestible material Humans and other mono gastric species cannot easily digest ungelatinized starch. Extrusion cooking is somewhat unique because gelatinization occurs at much lower moisture levels (12–22%) than is necessary in other food operations.

Processing conditions that increase temperature, shear, and pressure tend to increase the rate of gelatinization. The presence of other food compounds, particularly lipids, sucrose, dietary fiber and salts, also affects gelatinization. Complete gelatinization may not occur, but digestibility is improved nonetheless. Extrusion may pre-digest starch. Branches on amylopectin molecules are easily sheared off in the barrel. Reduction in molecular weight for both amylose and amylopectin molecules have been documented. The larger corn amylopectin molecules were subjected to the greatest molecular weight reduction. In a related study, wheat flour starch showed greater starch degradation after extrusion, and higher die temperature (185ºC) and feed moisture (20%) helped to maintain molecular weight. Screw configuration can be designed to minimize or maximize starch breakdown.

Rapidly-digested starch triggers rapid rise in blood sugar and insulin levels after meals. These increases may lead to insulin insensitivity and Type II, or adult-onset, diabetes. The rise in blood glucose after eating is often measured as the glycemic index (GI), with glucose or white bread used as an arbitrary control with a value of 100. High amylose rice extruded into noodles had lower starch digestibility and reduced GI in human volunteers. Higher GI values were found for persons with diabetes.

Extrusion conditions can be manipulated to produce digestion-resistant starch (RS) by several mechanisms. As branches are removed from amylopectin molecules, they could react with other carbohydrates in novel linkages that cannot be digested by our enzymes; such transglycosidation was observed in extruded wheat flour. A variation that adding certain forms of starch or citric acid to corn meal prior to extrusion process resulted modified resistant starch plus dietary fiber. Addition of 30% corn, potato or wheat starch did not increase RS values. RS and fiber values more than doubled when 7.5% citric acid was mixed with cornmeal, and 30% high-amylose cornstarch with 5 or 7.5% citric acid resulted in values of 14%, compared with slightly more than 2% in 100% cornmeal. The authors speculated that polydextrose may have been formed within the extruder. Cost and sensory acceptability were not determined. Oligosaccharides and polydextrose were formed from glucose- citric acid mixtures extruded at different barrel temperatures. Yields of polymers increased with temperature; 93.7% yield occurred at 200ºC. Added dietary fiber also affects digestibility. Longer cellulose fibers added to cornstarch decreased starch solubility.

On the other hand, addition of 20% protein with removal of insoluble dietary fiber from wheat flour resulted in pasta with significantly delayed dextrin release under *in vitro* digestion conditions (Fardet *et al.*, 1999). Microscopic evaluation indicated that fiber removal facilitated starch-protein interactions that may have increased enzyme-resistance.

Amylose-lipid complex formation can also reduce starch digestibility. Monoglycerides and free fatty acids are more likely to form complexes than are triglycerides when added to high-amylose starch Stearic acid mixed with normal corn starch with 25% amylose and extruded at low feed moisture (19%) and low barrel temperature (110–140ºC) contained the most starch-lipid complex.

The adverse nutritional consequences of easily-digested starch include increased risks for dental caries and rapid rise in blood glucose levels after eating. The smaller starch fragments formed during extrusion may be sticky and thus could adhere to teeth. Tooth pack, the amount of material retained on teeth after eating extruded foods, can be used as an indication of the severity of processing. Dental plaque bacteria rapidly ferment dextrins. White wheat flour extruded under ‘mild’ and ‘severe’ conditions caused drops in dental plaque pH comparable to glucose solution .The rate of sugars during extrusion cooking cannot be overlooked. Biscuits enriched with protein underwent sucrose hydrolysis during extrusion, with sucrose losses of 2–20%. Reducing sugars are presumably lost during Maillard reactions with proteins. Sucrose, raffinose and stachyose decreased significantly in extruded high-starch fractions of pinto beans. Extruded snacks based on corn and soy contained lower levels of both stachyose and raffinose compared to unextruded soy grits and flour, but values were not corrected for the 50–60% corn present. The destruction of these flatulence-causing oligosaccharides may improve consumer acceptance of extruded legume products.

Proteins and amino acids:

- Extrusion improves protein digestibility via denaturation, which exposes enzyme-access sites. Most proteins such as enzymes and enzyme inhibitors lose activity due to denaturation. The extent of denaturation is typically assessed as change in protein solubility in water or aqueous solutions.
- These changes are more pronounced under high shear extrusion conditions, although mass temperature and moisture are also important influences.
- For example, wheat protein solubility is reduced even at the relatively low process temperatures used in pasta making.
- Since most extruded foods are not high in protein, nutritional evaluations of extruded feeds, weaning foods and other specialized products have been

emphasized. High barrel temperatures and low moistures promote Maillard reactions during extrusion. Reducing sugars, including those formed during shear of starch and sucrose, can react with lysine, thereby lowering protein nutritional value. Lysine is the limiting essential amino acid in cereals, and further depletion of this nutrient can impair growth in children and young animals.

- Blends of cornmeal, full-fat soy flakes and soy isolates or concentrates produced nutritious ingredients suitable for reconstitution as porridge or gruel with good retention of lysine. Acidic pH increased Maillard reactions in a model system consisting of wheat starch, glucose and lysine.
- Soy protein has been identified as a cholesterol-lowering food ingredient. Extrusion texturization of soy isolate did not reduce its effects on rat serum cholesterol, excretion of cholesterol and other steroids in feces, or protein nutrition compared with non-extruded soy.

Lipids

- Generally foods containing less than ten per cent lipids are extruded because greater quantities of lipids reduce slip within the extruder barrel, making extrusion difficult, particularly for expanded products.
- Many extruded snack foods are fried after extrusion to remove moisture and modify texture and flavor. Response surface methodology was used to determine which extrusion parameters would limit oil absorption by a multigrain chip during frying. Oil content ranged from 20 to 35% as compared to a commercial product that has only 21% oil. Extrusion can be used to aid oil extraction since oil is freed during the cooking and shearing operations.
- Such obvious loss of lipids was first used to explain a mass balance dilemma in extrusion: extruded foods appear to contain lower lipid levels, formation of starch-lipid complexes resistant to some lipid extraction techniques. Lipid recovery is improved when extruded foods are first digested with acid or amylase, then extracted with an organic solvent such as ether. Total fat was not significantly changed in extruded whole wheat, but only half of the ether-extractable lipids in extruded was detected.
- After extrusion, wheat bran, which is lower in starch content than whole wheat, had more free lipids. Cornmeal extruded at 50–60ºC or 85–90ºC contained over 75% bound lipids, but extrusion at 120–125ºC only bound 70% of the lipids.
- Despite interest in health benefits of omega-3 fatty acids, another nutritional issue is the safety of *trans* fatty acids. Ex: extrusion of corn and soy resulted in formation of only 1.5% *trans* fatty acids.
- Lipid oxidation is a major cause of loss of nutritional and sensory quality in

foods and feeds, but lipid oxidation does not occur during extrusion due to brief residence time, lipid oxidation can occur during storage. Screw wear results in higher concentrations of pro-oxidant minerals. The iron and peroxide values were higher in extruded rice and dhal compared to dried products. Another factor favoring oxidation is the formation of air cells in expanded products, leading to increased surface area.

Dietary fiber

Dietary fiber is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation.

Extrusion did not affect uronic acids (components of pectin) but insoluble nonstarch polysaccharides (NSP) increased in oatmeal and potato peels. Soluble NSP was higher in extruded oatmeal and potato peels, and corn meal fiber was unaffected by extrusion. Beans subjected to conditions making them hard-to-cook, were extruded under various conditions in order to make them more functional.

Total fiber values were unaffected by extrusion but insoluble fiber decreased when extruded at 25% moisture content. Soluble increased in those samples, and especially in a sample processed at 30% moisture and 180ºC.

Ex:The viscosity of aqueous suspensions of extruded wheat, oats and barley were higher than unprocessed grains. Viscous gums and other soluble fibers may reduce cholesterol levels by trapping bile acids; increased excretion of bile eventually depletes body stores of cholesterol, which are tapped to synthesize new bile acids. Soluble forms of fiber such as those found in fruit and gums form gels in the small intestine. The increased viscosity is believed to retard the absorption of glucose, preventing spikes in post-prandial serum glucose levels.

Increased levels of soluble fiber in citrus peels after extrusion were correlated with increased*in vitro* viscosity. However, starch digestion and diffusion of glucose were not affected by extrusion. Extrusion reduced sugar beet pectin and hemicellulose molecular weight and viscosity, but water solubility increased 16.6% to 47.5%. Extrusion of guar gum in a wheat flake cereal did not impair the gum's ability to lower postprandial blood insulin and glucose levels in healthy adults.

Beta-glucans in oats and barley are believed to be responsible for thecholesterol-lowering properties of those grains. Solubility of -glucans in regular (Phoenix) and waxy (Candle) barley cultivars increased after extrusion at four barrel temperatures and three different moisture contents.

Vitamins

fortification of extruded foods with micronutrients is popular, little research has examined the interaction of extrusion conditions and nutrients. Concerns of reduced vitamin levels prompt some manufacturers to apply vitamins post-extrusion as a spray. More recent research has focused on vitamin stability in feeds. Fat-coated ascorbic acid, menadione, pyridoxine and folic acid were retained better than crystalline forms in extruded fish feed.

Folate is the most recent vitamin to be required for fortification and enrichment. The term folate is used to describe a family of related pteroylpolyglutamates and folic acid, a synthetic vitamin. Consumption of adequate folate by pregnant women and women of child-bearing age is recommended to prevent neural tube birth defects. Folic acid has superior bioavailability to folates found naturally in foods thus stability of folic acid in extruded foods should be evaluated.

Minerals

- High-fiber foods may abrade the interior of the extruder barrel and screws, resulting in increased mineral content.
- Potato peels extruded under higher temperature had as much as 38% more total iron after extrusion. Extruded corn, which is fairly low in fiber, showed no difference in total, elemental, or soluble iron, even in the presence of antioxidant additives.
- Iron content in extruded potato flakes increased with barrel temperature. Screw wear iron had high bioavailability in rats fed extruded corn and potato. Extrusion and any resulting changes in mineral content did not reduce utilization of iron and zinc from wheat bran and wheat in adult human volunteers.
- The solubility of iron under conditions similar to digestion and subsequent ability to dialyze across a membrane is used to assess bioavailability. Extrusion slightly increased iron availability in corn snacks.
- High-shear extrusion reduced dialyzable iron compared to low-shear extrusion of navy beans, lentils, chickpeas and cowpeas. Weaning foods based on pearl millet, cowpea and peanut had higher iron availability and protein digestibility than did similar foods prepared by roasting, however none of the blends provided adequate iron to meet infant needs.
- Extrusion did not compromise the zinc bioavailability of 85:15 blends of semolina and soy protein concentrate.
- Interest in nutrient fortification has led to addition of minerals to extruded foods, particularly cereals. Added calcium hydroxide (0.15–0.35%) decreased expansion and increased lightness in color of cornmeal extrudates, but

bioavailability of added calcium after extrusion has not been reported. Certain iron salts react with phenolics to form unattractive dark colors.

Non-nutrient healthful components of foods

- Phenolic compounds in plants protect against oxidation, disease, and predation. These compounds, including the large flavonoid family, are the focus of numerous studies to elucidate their role in human health.
- In potato peels, total free phenolics, of which chlorogenic acid predominates, were lower post-extrusion. Higher barrel temperature and feed moisture protected free phenolics.
- The red and blue anthocyanin pigments provide attractive colors and are believed to serve as antioxidants that protect vision and cardiovascular health.
- Blueberry anthocyanins were significantly reduced by extrusion and by ascorbic acid in breakfast cereals containing cornmeal and sucrose. Polymerization and browning may also have contributed to anthocyanin losses.

Antinutrients

Extrusion cooking destroys many natural toxins and antinutrients, There by improving safety and digestibility of the foods. Enzyme inhibitors, hormone-like compounds, saponins and other compounds may impair growth in children but may protect adults against chronic diseases. Compounds such as allergens and mycotoxins that are more resistant to heat and shear may be susceptible to extrusion in combination chemical treatments.

Glucosinolates are found in many commercially-important *Brassica* species, and may have a role in cancer prevention. Extrusion alone likely has little effect on retention of glucosinolates. Canola total glucosinolates were reduced by added ammonia during extrusion. Although extrusion with ammonium carbonate did not completely destroy glucosinolates in rapeseed meal, the process did improve nutritional parameters in rats fed the extruded versus unprocessed rapeseed meal.

Soy isoflavones have estrogenic activity, and thus may protect post-menopausal women from osteoporosis and heart disease, while men may receive protection against prostate and other testosterone-dependent cancers. Okara, a by-product of tofu manufacture, was mixed with wheat flour and evaluated for retention of isoflavones. Two barrel temperatures and screw configurations were tested. The aglycone genistein significantly decreased under all extrusion conditions, and glucosides of daidzin and genistin increased, presumably at the expense of acetyl and malonyl forms. Total isoflavone values were significantly lower in 40% okara samples extruded at high temperature.

Lecture: 11

Practical considerations in extrusion processing: pre-extrusion processes, cooker extruder
Profiling