A review of a machine design of chocolate extrusion based co-rotating twin screw extruder

P Pitayachaval and P Watcharamaisakul

School of Industrial Engineering, Institute of Engineering, Suranaree University of Technology, 111 University Avenue Muang, Nakhon Ratchasima, Thailand

E-mail: paphakorn@g.sut.ac.th

Abstract. Based on innovation and competitive market for food industry, there are several food products which have been designed to attract customer. Since there is USD 39,431 millions of chocolate sales in 2018, USA [1], chocolate product shapes have been developed based on manufacturing process. This paper presents a review process of a machine design of chocolate extrusion based co-rotating twin screw extruder. A property of suitable chocolate for extruder was established. The pros and cons of machine extruder for food processing including, a screw extruder design were exposed. Since there were problems in the chocolate extruder, the process parameters such as barrel temperatures, feed rate, screw speed, motor load and melt pressure were established. These parameters would be applied to design screw extruder for chocolate processing.

1. Introduction
Several new technologies or innovations have been introduced in order to increase productivity while reducing production cost. There are several areas in food industry that have high competition, such as, the chocolate market which has market of USD 39,431 millions of chocolate sales in 2018 in USA with consumers ranging from children to adults [1]. Therefore, many technologies have been applied to increase productivity of chocolate production while enraging flavors and various shapes. Since the properties of chocolate are melted in normal temperature, flowed in a container and changed viscosity depending on the temperature, chocolate is processed via many production processes such as extrusion, printing, and so on. However, there are several problems during extrusion process such as low productivity rates, product waste and improper extrusion temperature affect to increase production costs. Therefore, the chocolate extrusion is processed with the screw extruder in order to reduce those problems, and the screw extruder has been applied to control various factors including high flexibility. This paper presented a review process of a machine design of chocolate extrusion based co-rotating twin screw extruder.

2. Chocolate
Chocolate is composed of nonfat particles (sugar, cocoa solids, and milk powder particles) dispersed in cocoa butter as a continuous phase [2]. The flow properties to control the quality of chocolate product of a chocolate flow is an important parameter since too low viscosity will cause the weight of the chocolate over the enrobed candy will also be too low. However, if it is too high, then bubbles may be formed and put chocolate. Moreover, the different chocolate viscosity provides distinguished
flavor, that can be detected by consumers. The perceived taste is related to the viscosity and rate of melt. Therefore, the flavor of chocolate is different between stored in the refrigerator or in a room temperature [3]. Therefore, the designs of the machine to process chocolate are important to control the parameters that affect the flow and viscosity of chocolate. Those factors affect the chocolate extrusion process because they are involved in melting, as well as extrusion through the die.

3. Extrusion processing in food industrial
The extrusion processing for the food industry has been wildly used in production process since it provides a variety of food shapes. The products vary depending on the ingredients and the condition of the control. The Machine, called Extruder, has been incorporated with various processes. The extruder mechanism is to blend raw materials and ingredients (feed or transport section) under pressure and heat conditions to shape or meter the section from compression, and to push the product out to die. Extrusion technology has been introduced to shape a variety of food productions because there are many advantages such as saving energy, reducing labor and production costs, flexibility for several raw materials, ability for mixing ingredient, and saving space for tool installation. Those properties can also improve the quality of products as needed [4].

4. Screw extruder design
Hot-melt extrusion equipment consists of an extruder, auxiliary equipment for the extruder, downstream processing equipment, and other monitoring tools used for performance and product quality evaluation [5]. The extruder is typically composed of a feeding hopper, barrels, single or twin screws, and the die and screw–driving unit (figure 1). The auxiliary equipment for the extruder mainly consists of a heating/cooling device for the barrels, a conveyer belt to cool down the product and a solvent delivery pump. The monitoring devices on the equipment include temperature gauges, a screw-speed controller, an extrusion torque monitor and pressure gauges.

![Figure 1. Micro-18 Twin screw co-rotating Leistritz extruder](image)

The theoretical approach to understanding the melt extrusion process is generally presented by dividing the process flows into four sections, as follows [7]: 1) Feeding of the extruder, 2) Conveying of mass (mixing and reduction of particle size), 3) Flow through the die, 4) Exit from the die and down-stream processing. Generally, the extruder consists of one or two rotating screw inside a stationary cylindrical barrel. The barrel is often manufactured in sections, which are bolted or clamped together. An end-plate die, connected to the end of the barrel determines the shape of the extruded product shown in figure 1 and figure 2.
The heat that is generated from friction force is required to melt or fuse the material. This force is a shear force occurring between the rotating screws and the wall of the barrel that is mounted with electric or liquid heaters [8]. Most commercial extruders have a modular design, providing a choice of screws or interchangeable sections which modify the configuration of the feed, transition, and metering zones. The modular design has been introduced to meet special process requirements, such as, increase high shear extrusion, addition more solvent and enlarge evaporate solvent from raw material. Modifying screw designs also allow the extruder to perform a mixing and reduction of particle size in addition to extrusion, so that material can be blended into the extrudate or even dissolved, as shown in figure 3.

The screw and die design was available, and a practical considerations of thermoplastic extrusion were reviewed by Whelan and Dunning [9]. The extrusion channels were conventionally divided into three sections: feed zone, transition zone, and metering zone, as shown in figure 4. The starting material was fed from a hopper directly into the feed section, which has deeper flights or flights of greater pitch, as shown in figure 5. This geometry enabled the feed material to fall easily into the screw for conveying along the barrel. The pitch and helix angle determined the throughput at a constant rotation speed of the screws. The material was transported as a solid plug to the transition zone where it was mixed, compressed, melted and plasticized. Compression was developed into two types: (1) decreasing the thread pitch while keeping a constant flight depth, and (2) decreasing flight depth but keeping a constant thread pitch [10]. Both types resulted in increasing pressure as the material moved along the barrel. The melt conveyed by circulation in a helical path by means of transverse flow, drag flow, pressure flow and leakage; the latter two mechanisms reversed the flow of material along the barrel. The space between screw diameter and width of the barrel is normally in the range of 0.1-0.2 mm [8]. The material reaches the metering zone in the form of a homogeneous plastic.
melt suitable for extrusion. To extrude a uniform part thickness, flow must be consistent without stagnant zones right up to the die entrance. The function of the metering zone is to eliminate pulsating flow and ensure a uniform delivery rate through the die cavity [7].

5. Twin screw extrusion
The twin-screw extruder has two agitator assemblies mounted on parallel shafts. These shafts are driven through a splitter/reducer gearbox and rotate together in the same direction of rotation (co-rotating) or in the opposite direction (counter rotating) and are often fully intermeshing. In such case, the agitator element wipes both the surface of the corresponding element on the adjacent shaft, and the internal surfaces of the mixing chamber and ensures a narrow and well-defined residence time distribution. In general, co-rotating shafts have better mixing capabilities as the surfaces of the screws move towards each other. This leads to a sharp change in mass flow between the screw surfaces [7]. As the screws rotate, the flight of one screw element wipes the flank of the adjacent screw, causing material to transfer from one screw to the other. In this manner the material is transported along the extruder barrel. The twin-screw extruder was characterized by the following descriptive features [8]:

1) Short residence time: The residence time in the twin-screw extruder in a typical extrusion processes ranges from 5–10 minutes depending on the feed rate and screw speed, 2) Self-wiping screw profile: The self-wiping screw profile is the flight of the one screw wipes the root of the screw on the shaft next to it, ensures near complete emptying of the equipment and minimizes product wastage on shutdown, 3) Minimum inventory: Continuous operation of the equipment coupled with the continuous feeding of the material helps in reducing inventories of work in progress. This is important when processing valuable or potentially hazardous materials, 4) Versatility: Operating parameters can be changed easily and continuously to change extrusion rate or mixing action. The segmented screw elements allow agitator designs to be easily optimized to suit a particular application. Die plates can also be easily exchanged to alter the extrudate diameter. This allows processing of many different formulations on a single machine, leading to good equipment utilization. Polymers with a wide range of viscoelastic and melt viscosities may be processed and even fine powders may be directly fed into the system, 5) Superior mixing: The screws have various mixing elements which impart two types of mixing, distributive mixing and dispersive mixing. The distributive mixing ideally maximizes the division and recombine the material while minimizing energy. The dispersive mixing ideally breaks droplet or solid domains to fine morphologies using energy at or slightly above the threshold level needed. This mixing aids in efficient compounding of two or more materials in the twin-screw extruder.

Typical twin-screw laboratory scale machines have a diameter of 16-18 mm and length of four to ten times the diameter. A typical throughput for this type of equipment is 0.5–5 gm/min. As the residence time in the extruder is rather short and the temperature of all the barrels are independent and can be accurately controlled from low temperatures (30°C) to high temperatures (300°C), degradation by heat can be minimized [8]. Extrusion processing requires close monitoring and understanding the various parameters: viscosity and variation of viscosity with shear rate and temperature, elasticity and extensional flow over hot metal surfaces. Today, extruders allow in-process monitoring and control of parameters, such as the temperature in the extruder, head and die as well as pressure in extruder and die [11].

6. Extrusion parameters
The main monitoring and controlling parameters are barrel temperatures, feed rate, screw speed, motor load and melt pressure. Barrel temperature, feed rate and screw speed are controlling parameters and motor load and melt pressure are monitoring parameters. 1) Barrel temperatures: The glass transition or melting temperatures of polymers and drug usually determines the barrel temperature, 2) Feed rate and screw speed. The constant feeding rate and screw speed throughout the process is important as the combination of these two factors establishes the level of fill in extruder. This is critical to the process, because it governs the balance between the weak and strong mass transfer mode [8]. Due to constant feed rate and screw speed, there will be a constant amount of material in the extruder and thus the
shear stress and residence time applied to material remains constant, 3) The motor load and melt pressure: These parameters depend on feed rate and screw speed. With constant feed rate and screw speed these parameters depend upon the molecular weight of polymer and drug as well as polymer miscibility in binary mixtures [7].

7. Co-rotating and counter rotating twin screw

Since there are varieties of raw materials to mix into chocolates, the co-rotating twin screw extruders has been interesting to investigate in order to improve chocolate extruder machine. The twin screw extruder has been classified into two types as following [12]: 1. Based on screw rotation direction: co-rotating and counter-rotating, as shown in figure 6, 2. Based on degree of meshing: non overlap (non-intermeshing) and overlaps which are a partially intermeshing and a fully intermeshing as shown in figure 7.

The range of twin screw extruder operation is during low speed (10-40 rpm) to high speed (200-500 rpm). In most industries, counter-rotating twin screw extruders are preferred because they have better conveying performance than co-rotating twin screw extruders as well as counter-rotating twin screw extruders and the heat generated by the shear is less [12].

Figure 6. Screw rotation direction, co-rotating screw and counter-rotating [6]

Figure 7. The amount of overlap between the screws in the twin-screw extruder [6]

Twin screw extruder offers advantages over single screw extruder in that it does not require a drag force to push the material. Less shear results in less shear heat, more efficient mixing and less flexibility for low speed applications [6]. A comparison of screw parameters was concluded as table 1.
Table 1. A review of investigating screw parameters.

| Researchers                  | Year | Single screw extruder | Twin screw extruder | Ram extruder | Screw speed | Material temperature |
|------------------------------|------|------------------------|---------------------|--------------|-------------|----------------------|
| Milivoje M. Kostic [14]      | 2006 | die design             | -                   | -            | -           | -                    |
| Vivar-Vera [15]              | 2008 | -                      | -                   | -            | 40–60rpm    | 40-80°C              |
| HesamAnvariArdakani [16]     | 2014 | -                      | -                   | -            | -           | 30-50°C              |
| Chris Rauwendaal [1]         | 2015 | solving extrusion problems | -                     | -            | 50 rpm      | 50 - 100°C           |

8. Screw extrusion problems

Although there are several benefits of screw extrusion e.g. available for many chocolate formulas, flexible for process parameters and suitable for continuous process, there are many extrusion problems such as shape accuracy, appearance problems, functional product properties, high melt temperature, high motor load, wear of screw and/or barrel. Moreover, process problems had been mentioned [1] such as low yield productivity, and products defected, as shown in figure 8. A non-appropriate extrusion temperature affects to product surface that increases production cost, as shown in Figure 8(a), and to chocolate state that constructs un-uniform chocolate line, as shown in figure 8(b).

(a) The cracks surface
(b) Un-uniform chocolate line

Figure 8. Defective product [13]

9. Future experimental design

Based on the literature reviews, the temperature and screw speed parameters affected the product shape and flaw. However, there were a few studies on twin screw condition. In order to improve product development, the co-rotating twin screw extrusion will be investigated as a future work to determine suitable conditions such as screw speed and appropriate temperature for extrusion process. The co-rotating twin screw for chocolate extruder will be conducted based on two parameters that are screw speed and temperature in barrel. Then, the width of the extruded chocolate lines and the error between extruded chocolate and nozzle diameter will be measured as the results in which the design tolerance will be controlled with in ± 0.1 millimeters.

10. Conclusion

Screw extrusion is widely used in the food industry e.g. pasta and dessert. One of the desserts with high market value is chocolate, in which chocolate is also capable of melting and extrusion. The extruder also has many problems in the manufacturing process, such as low productivity and defective products. As a result, the extruder design has been investigated to improve process efficiency and reduce the production problems that occurred during extrusion process. The co-rotating twin-screw extruder has been redesigned in order to reduce product flaws while increase productivity. Since co-rotating twin-screw composes of feeder element, transition element and metering element, the advantages of co-rotating twin-screw are well mix chocolate paste and good conveying performance of paste products. However, the process parameters of co-rotating twin-screw chocolate extrusion should be investigated in order to minimize screw extrusion problems as a future work.
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