Different types of fryers for the food industry

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10.1 Introduction

Frying is an age-old processing technique, with a pan or a pot being its essential tool. The amount of oil or fat used, level of heat, frying time, and even the style of stirring, have set the foundation for many different frying methods. This in turn has given way to developing different fryers, starting with pans of different shapes and sizes, and continuing with a wide selection of electrical automated equipment. While some fryers mimic existing practices, like deep fryers or automated stir fryers, others offer alternative approaches, like air, vacuum, or pressure fryers. Thus, this chapter starts by introducing traditional frying methods and their currently available fryer types and will continue by focusing on alternative fryer options.

In addition to an overview of conventional and alternative fryer types, the chapter will elaborate on them based on different production scales. Domestic kitchen fryers are meant for light use and they should not take up much kitchen space; whereas, commercial fryers are designed for more intense use in the foodservice sector for serving customers and are thus bigger in size and more sturdy. Domestic and commercial frying are commonly batch processes, meaning that a specific amount of food is fried at once. For example, pan-frying is a batch process in which food is loaded into the pan, fried, and removed from the pan when ready. Afterward, another batch of food could be fried. In addition to commercial batch fryers, this chapter will explore their currently available continuous versions as well, where food goes continuously in from one end of the fryer and exits from the other end, fried. On the other hand, industrial batch or continuous fryers are meant for large-scale production of fried products, not for direct consumption, but to be packaged and distributed, which might end up as finished products in retail stores or intermediate products in food services.

Compared to one another, fryers have their advantages and disadvantages, such as price, size, frying speed, operating complexity, production capacity, end-product taste, texture, and heath, which become decisive in the most suitable fryer selection and oftentimes also drive fryer development and innovation. Thus, different fryer advantages and disadvantages will be compared in more detail under fryer selection, followed by insights into fryer development in food industries and current fryer innovation.

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10.2 The conventional type of fryers

The terms “shallow” and “deep” are often used to categorize frying methods, which indicate the amount of oil used during these processes. During deep-frying, food could be completely submerged into the oil. While in comparison, shallow frying, also referred to as pan-frying, uses significantly smaller amounts of oil, either to just grease the utensil surface or leave a visible layer of oil or fat (The Culinary Institute of America, 2011; Myhrvold et al., 2011; Davidson, 2006).

10.2.1 Pan fryer

Shallow or pan-frying are often used as general terms, which include frying methods like pan-frying, stir-frying, and sautéing. Although in one context the terms pan- and shallow frying might be used interchangeably, in another, they might be differentiated by the amount of oil or fat used (The Culinary Institute of America, 2011; Myhrvold et al., 2011; Davidson, 2006). Regardless, this does not affect the type of fryers used. For the sake of clarity, this book will use “pan fryers” as the umbrella term for the fryers under this category although some modern alternatives might not look like a pan at all!

According to the Culinary Institute of America, pan-frying is “A cooking method in which items are cooked in deep fat in a skillet; this generally involves more fat than sautéing or stir-frying but less than deep-frying” (The Culinary Institute of America, 2011). Sautéing and stir-frying are both quick cooking methods using small amounts of fat. Unlike sautéing, stir-frying includes tossing using a traditional wok or, nowadays, a stir-fry pan alternative. Wok is a bowl-like frying pan, which enables tossing of food during stir-frying with minimal spilling (The Culinary Institute of America, 2011; Myhrvold et al., 2011; Davidson, 2006).

Pans come in different shapes, sizes, and materials. Materials used for pans include stainless steel, aluminum, copper, cast iron, and carbon steel. Pans can also be coated with different materials, including Teflon, ceramic, and porcelain enamel. According to the amount and type of food being cooked and the frying method used, pans differ in diameter, bottom thickness, and shape, giving rise to different types of pans, like skillets, frying, roasting, stir-fry, sauce, and sauté pans, and woks (Drysdale, 2009; Zeb, 2019).

Pans can be used with electrical or gas induction heating. In the case of induction heating, pans should contain or be made out of ferromagnetic material to heat up. An induction stove heats only the part of the pan in contact with the stove (Drysdale, 2009). Since the wok is meant to be used in flames, heating up the sides as well, induction woks need a deeply curved induction stove where the wok would fit completely inside, which would enable the wok to heat from both the bottom and the sides. An example of an induction heated wok pan stove can be seen in Fig. 10.3 (Shanghai Chuanglv Catering Equipment Co., Ltd, 2020).

Griddles could be used to replace pans in a commercial setting (Fig. 10.1). A griddle is a heavy, metal surface, which has heaters directly under it. Cooking is done

Fig. 10.1 Flat commercial griddle.
Courtesy of Ottoman Mutfak, Istanbul, Turkey.

directly on the griddle after greasing the surface with a little bit of oil. Since griddles do not have sides like pans do, it is easier to flip food and they do not hold water near the frying food, allowing it to be properly seared. Griddles have a large surface area, which enables them to cook a large amount of food compared to a pan. Therefore, they are mainly used in the foodservice sector, but smaller ones exist for domestic use as well (The Culinary Institute of America, 2011; Myhrvold et al., 2011; Drysdale, 2009).

Besides pans, automated electrical batch and continuous fryers meant to imitate pan-frying cooking methods have also been developed. As mentioned above, stir-frying and sautéing require less oil, higher heat, and shorter cooking times compared to pan-frying. While all of the techniques require stirring to some extent, stir-frying requires constant tossing of food. Thus, in order to mimic these practices, automated pan fryers should enable mixing at different speeds or even tossing of the food, in addition to having adjustable heating temperatures and oil amounts. It is important that these fryers are able to maintain a high temperature after food is added to the frying vessel and that mixing only causes minimal breakage of the food.

Different ways in which automated pan fryers can mix food are by tumbling, paddling, tossing, or with a horizontal stirring screw. Tumbling type fryers include a hollow ellipsoidal frying vessel that can be tilted to a suitable angle. The amount of oil and food used can be adjusted by the operator who adds them from the opening in front of the tank. The vessel is heated, rotates, and has protruding elements attached to its inner wall to enable uniform frying through even mixing. According to the frying vessel's capacity, tumbling type fryers can be used for domestic, commercial, or even industrial purposes. Since the frying vessel's temperature and rotating speed can be adjusted, the fryer can be used for various pan-frying techniques. Since some of these fryers are specially designed to accommodate the extreme condition of stir-frying, they are called stir fryers (ANKO Food Machine Co., LTD, 2020; Ding-Han

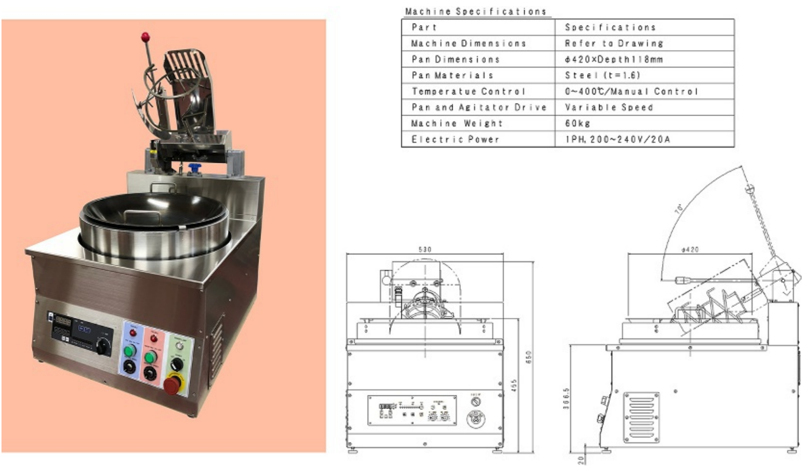
Fig. 10.2 Batch pan fryer with a central stirring blade.
Courtesy of GEA Group, Düsseldorf, Germany.

Machinery Co., Ltd., 2020a; German Pool Group Co. Ltd, 2020; DANENG (S) Energy-Saving Technology Pte Ltd, 2020).

In the case of a batch pan fryer in which mixing is done through paddling (Fig. 10.2), the frying vessel lays horizontally. The food and oil are added to the heated frying vessel from the opening at the top by the operator. The fryer in Fig. 10.2 has a stationary frying vessel with central blades to stir the food (GEA Group, 2020).

Some of the batch pan fryers are designed especially to accurately mimic the tossing of the stir-frying process to ensure minimal breaking of food (Figs. 10.3 and 10.4). The wok pan in Fig. 10.3 is induction heated and rotates. The pan is heated, oil and food are added, after which the stirrer is lowered, which tosses the food as both the pan and stirrer rotate (IKC Asia-Pacific Pte Ltd, 2020).

The stir fryer in Fig. 10.4 has a horizontal rotating frying vessel with a tossing stirrer on one side, which picks food up from its one side and, with a circular movement, puts it down on the other side. Since it is an open vessel and the stirrer is only at one side, the operator could also easily intervene in the process by mixing or scraping any stuck food with a spatula. This minimizes food breaking during tossing and ensures uniform frying (IKC Asia-Pacific Pte Ltd, 2020).



Part	Specifications
Machine Dimensions	Refer to Drawing
Pan Dimensions	Φ420×Depth118mm
Pan Materials	Steel (t=1.6)
Temperatue Control	0~400℃/Manual Control
Pan and Agitator Drive	Variable Speed
Machine Weight	60kg
Electric Power	1PH, 200~240V/20A

Fig. 10.3 Batch stir fryer with the stirrer raised up *(left)* and its schematic drawing with the stirrer lowered into the wok pan *(right)*.
Courtesy of IKC Asia-Pacific Pte Ltd., Singapore.

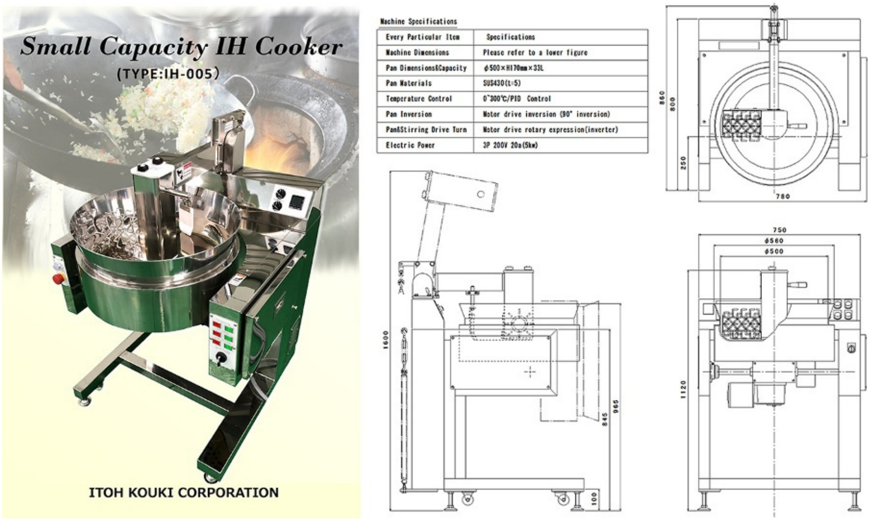


Fig. 10.4 Batch stir fryer with a tossing stirrer *(left)*, its schematic drawing from above *(center)* and the side, with a side view of the stirrer (*right)*.
Courtesy of IKC Asia-Pacific Pte Ltd., Singapore.

In addition to commercial batch pan fryers, industrial-scale versions are also available. An example would be a fryer with a horizontal cylindrical frying vessel with a stirring screw in the middle (Fig. 10.5). The stirring screw allows sudden forward and reverses movements, which enables it to mimic the stir-frying tossing motion. It is important that food do not stick to the frying vessel and accumulate there, which would result in uneven frying. Thus, these types of frying vessels should also include special built-in scrapers. Furthermore, in some cases, it is possible to modify the size of the frying vessel to enable frying smaller batches. Some of these types of fryer options can even be adjusted for vacuum stir-frying (Blentech Corporation, 2020).

Some batch pan fryers can be adjusted to enable continuous industrial-scale frying. Like the previous batch fryer, the continuous fryer contains a screw in the frying vessel

Fig. 10.5 Close-up of the stirring screw of an industrial-scale batch or continuous pan fryer.
Courtesy of Equipment Exchange, Pennsylvania, United States.

to enable horizontal stirring, with food inlet at one end and the outlet at the other. Depending on the model, these kinds of fryers can also be accommodated to allow pan and deep-frying and blanching or boiling (Blentech Corportion, 2020).

10.2.2 Deep fryer

Compared to the variety of pan-frying methods, deep-frying is straightforward. It is important that there is enough oil to cover the product so that it can be submerged in the oil, turned easily in the oil if it is floating, or pushed under the oil. Thus, a deep fryer should be able to heat a large amount of oil and maintain its temperature. However, to enable cost-efficient production, the oil should be maximally reused. Thus, it is important to consider aspects like oil circulation, filtration, and usage duration, to prevent oil decomposition or harmful compounds from forming (Drysdale, 2009; Mallikarjunan et al., 2009; Zeb, 2019).

Domestic deep fryers are usually countertop batch versions, whereas commercial ones could be either countertop or floor-type (Fig. 10.6). Both domestic and commercial batch fryers have strainers, which hold the food. Together with the strainer, food is lowered into the oil and, when ready, it is lifted out. Automatic deep fryers include an elevator system, which lifts the strainer out by itself. The strainer is then left to strain the oil from the product as can be seen in Fig. 10.6 (Ottoman Dış Ticaret ve Mutfak Gereçleri Pazarlama LTD. ŞTİ, 2020).

Fig. 10.6 The floor-type commercial batch deep fryer.
Courtesy of Ottoman Mutfak, Istanbul, Turkey.

Fig. 10.7 Standalone commercial batch deep fryer unit.
Courtesy of Ottoman Mutfak, Istanbul, Turkey.

Some commercial deep fryer units might contain a separate area to store already fried products, as can be seen on the left of Fig. 10.7. The perforated pan allows extra oil to drain, while heating lamps above keep the products warm. In addition, some commercial deep fryers have different frying programs, with varying frying time and temperature for different products, which makes it possible to get uniform quality products with less operator expertise (Ottoman Dış Ticaret ve Mutfak Gereçleri Pazarlama LTD. ŞTİ, 2020).

It is important to remove crumbs from fryer oil to prevent them from degrading and diminishing oil quality and usage time (Erickson, 2007). Although common in industrial fryers, even commercial fryers may have an oil filtration system, which works by opening a valve at the bottom of the frying oil vessel, allowing the oil and crumbs to flow through a perforated metal plate containing a filter that catches the crumbs, to a container underneath it. After all the oil has been removed from the frying vessel, the filtered oil is pumped back up through a pipe connected with the frying vessel. This system makes it possible to safely clean the frying vessel and filter the oil without spills and taking up too much time and space in the kitchen (Ottoman Dış Ticaret ve Mutfak Gereçleri Pazarlama LTD. ŞTİ, 2020).

Industrial-scale batch fryers are similar to domestic and commercial deep fryers because they include a frying vessel holding the oil and a removable strainer (Fig. 10.8). However, in accordance with the scale of production, the frying vessel is bigger and the fryer includes special mechanisms to lift the heavy strainer (Economode Food Equıpment (India) Pvt. Ltd., 2020). In some cases, batch fryers

Fig. 10.8 Rectangular industrial batch deep fryers.
Courtesy of Economode Food Equipment India Pvt. Ltd., Maharashtra, India.

are preferred to continuous deep fryers because they give specific characteristics to the product (PotatoPro, 2020).

In comparison to conventional batch deep fryers, wider batch deep fryers are also available to fry bigger products, like eggplants, fish, or doughnuts. For example, their width enables them to fry multiple doughnuts at once. A flat strainer plate is used to place the doughnuts in the oil and remove them. Since doughnuts float on oil, they need to be turned around to evenly fry both sides. In the case of batch fryers, the operator has to turn the doughnuts manually (Ottoman Dış Ticaret ve Mutfak Gereçleri Pazarlama LTD. ŞTİ, 2020). Continuous doughnut fryers include a long pool of oil, in which the doughnuts float. The pool has either a constant oil current or metal blades, which force the products to move forward. After one side has been properly fried, a wide metal blade automatically turns the doughnuts around to be fried from the other side (Heim Gerätebau GmbH and Co., 2020).

Continuous deep fryers are typically used for large-scale production but smaller commercial versions have also been developed (Ding-Han Machinery Co., Ltd., 2020b). Continuous fryers often include a conveyor belt to move the products along with the oil and in some cases two conveyor belts on top of each other to keep floating products submerged in oil. To get the same quality of product throughout the frying process, the fryer should enable precise side-to-side and end-to-end oil temperature control to avoid any unintended temperature changes. Continuous fryers are usually equipped with systems to remove food crumbs, which either float or sink to the bottom of the oil. Depending on the products, built-in or separate oil filtrations systems can be used to remove impurities enabling the reuse of oil (Fig. 10.9). Since some oil is absorbed by the products during frying, continuous fryers should have systems in place to measure oil level and add oil when required (Erickson, 2007; Sumnu and Sahin, 2008; Mallikarjunan et al., 2009).

Fig. 10.9 Continuous industrial deep fryer.
Courtesy of Economode Food Equipment India Pvt. Ltd., Maharashtra, India.

10.3 Alternative types of fryers

In the development of frying technology, conventional fryers including pan fryers and deep fryers have been used for centuries. Nevertheless, both frying systems suffer disadvantages, such as high oil uptake and acrylamide formation of final fried products due to high frying temperatures and the large amount of frying oil used. Because health concerns among modern consumers are growing, oil content and acrylamide reduction are the main issues in the improvement of frying technology. Thus, alternative types of fryers such as pressure fryers, vacuum fryers, air fryers, and microwave fryers have been developed to provide a higher quality of fried foods than conventional fryers.

10.3.1 Pressure fryer

The pressure fryer is one of the most common and popular commercial fryers in the fast food industry, especially for fried chicken products. It is well-known that a higher quality of fried product is produced by pressure frying equipment than by an open deep fryer under atmospheric pressure. The pressure fryer was initially designed for fried chicken in fast-food chain restaurants to obtain tender and crispy meat texture within a short time. Because of the demands on fast-food restaurants, the fried chicken is required to have a rapid cooking process and short service time. Some frozen par-fried foods and prepared foods with specific recipes are recommended to cook at a specific pressure. Even though the pressure fryers provide a limited application for large-scale production, the unique flavor and taste after pressure frying are still highly desired by consumers (Mallikarjunan et al., 1997; Mohan Rao et al., 1995).

During the pressure frying process, the moisture inside the foods is released to increase inner pressure in the frying vessel. However, the application of nitrogen gas is used to reach desirable high pressure inside the fryer instead of the pressure generated from the steam from food moisture. Commercial breaded chicken breast nuggets were fried at two pressures (163 and 184 kPa) and three frying temperatures (150°C, 175°C, and 190°C) with two sources of pressure, that is, generated from nitrogen gas and steam caused by moisture of the fried products. The results showed that the frying under nitrogen gas offered the higher quality of fried products in comparison with the pressure source from steam due to the increase of moisture retention, juiciness, and texture preference in the final fried products (Innawong et al., 2006).

The texture of fried products is also influenced by any surface coating on the foods. For the breaded fried chicken nuggets, the whey protein isolate-coated samples frying under a steam environment were crisper comparing with nitrogen gas; whereas uncoated and methyl cellulose-coated samples using nitrogen gas as the pressure source were crispier than using steam. It indicated that the film-forming property of coating materials on fried products is significantly affected by the different pressure sources during the frying process (Ballard and Mallikarjunan, 2006; Sumnu and Sahin, 2008). On the other hand, chicken nuggets were fried at 175°C and 163 kPa for 4 min with a modified restaurant-type pressure fryer under nitrogen gas and steam as pressure sources. Consumer assessment for the fried breaded chicken nuggets was conducted by untrained human subjects. In this case, no significant preferences between these samples were exhibited in terms of oiliness, juiciness, flavor, and crispness (Ballard et al., 2007).

The pressure fryer can be constructed as a batch type or a continuous type with an electric or gas heating system of many different designs. When starting the pressure frying process with a sealed lid, the raw materials are heated and moisture released from the frying materials to become steam, which fills the air space of the frying chamber, thus increasing the inner pressure. The moisture comes out from fried materials continuously until the inner air holds water steam at the maximum level, reaching complete air saturation.

Because moisture content can be maintained within the food materials under the saturated water vapor environment, the final fried products are noticeably juicy, tender, and crispy. In addition, some volatile aroma compounds of foods can be much better preserved within fried products under the high-pressure frying process. However, moisture retention may cause frying oil rancidity rapidly because oils and fats undergo oxidative reactions partially or completely after exposure to moisture. The oil degradation results in the adverse formation of unfavorable compounds, which can affect consumer preferences and purchase decision-making (Mallikarjunan et al., 2009).

There are two types of batch pressure fryer, countertop type and floor type, in restaurants or catering industries. For countertop fryers, the heat capacity ranges from 7.5 to 13 kW. The oil capacity of fryer vessel can be 7 to 15 L with a single basket and gas or electrical heating system with a temperature monitor to heat the oil up to 210°C and cut off the heating source automatically to allow oil temperature cool down to 95°C within a few minutes in the frying vessel. During the pressure frying process, the operating pressure can reach approximately 105 kPa. These countertop fryers are used very commonly for small-scale production in restaurants and pilot plants because the operation is convenient, with a single pressure setting, simple temperature monitoring, and automatic heating turn-off (Gupta, 2004).

Floor-type fryers are also widely used for small- or middle-scale frying production, as they have larger frying vessels than countertop fryers. The heat capacity of these fryers ranges from 25 to 60 kW. The oil capacity of the fry container can be 20 to 40 L. These fryers are also normally equipped with electrical or gas heating systems that enable rapid heat recovery. When the demand for fried products is low, for example, between meal times or at night, the fryer can be set on standby mode. It is very important to allow the frying oil temperature to drop quickly and then let it recover gradually for gaining desirable flavor, texture, and appearance of the final fried product, especially for fried meat, fish, and chicken products. In order to prevent foodborne illness outbreaks and obtain the desired quality of fried products, the oil temperature must be controlled and monitored precisely and prudently (Gupta, 2004).

The first prototype of a pressure fryer was developed in 1917 by The United States Department of Agriculture (USDA) after the first patent of a pressure cooker was granted in 1902. However, it was not widely used until 1935. The first commercial pressure cooker was produced and released onto the market in 1939. Afterwards, it was modified into a pressure fryer by a fried chicken producer to provide high-quality fried products in their restaurants. The first model of pressure fryer was equipped with a jiggle top vent at a single pressure setting of 15 psig (lbs/in^2). However, these appliances with this depressurization system could cause operational safety issues. The modern design of pressure release system is a spring-loaded system equipped with a safety alert indicator. This mechanism of pressure controlling not only makes it easy to adjust the inner pressure, but is also safe to depressurize when the frying process is complete.

A floor-type stainless steel pressure fryer with 11 kW thermal power electrical heating system manufactured by Ottoman Mutfak Ltd. (Istanbul, Turkey) is shown in Fig. 10.10 (left). Its 45 L tank reservoir with 25 L oil capacity allows the frying of 30 chicken drumsticks or 50 to 60 chicken wings in one batch frying process. This pressure fryer is equipped with a digital display controller with 10 different programs, a sliding cover system, and an automatic micro stainless steel oil filter. For safety control, there are three mechanical and one electric safety control with audible and visual warning systems. Moreover, it contains an automatic pressure relief system in the event of a pressure jam. Another, automatic model of pressure fryer, similar to the fryer mentioned above but more advanced, and manufactured by the same company, is shown in Fig. 10.10 (right). The significant highlight of the later advanced model is the highly automatic and larger capacity of frying. It contains a four-layer tray basket to increase frying capacity up to 50 chicken drumsticks for one batch frying process. Furthermore, automatic sealed frying vessel and pressurization systems make frying operation more efficient and effective in comparison with the previous model.

10.3.2 Vacuum fryers

Vacuum frying technology was first developed in the late 1960s, when it was used to produce potato chips. Comparing with the traditional frying process, the products produced by vacuum frying are much more desirable. Since the 1980s, vacuum frying technology has developed rapidly and is widely used, especially in East and Southeast

Fig. 10.10 Two modern models of floor-type pressure fryers: manual-loaded *(left)* and automatic-loaded *(right)*.
Courtesy of Ottoman Mutfak, Istanbul, Turkey.

Asia including Taiwan, Philippines, Indonesia, China, and Thailand. Slices of fruits and vegetables cooked under the vacuum frying process have become very popular fried products. Commonly vacuum-fried vegetables include carrots, okra, sweet potato, potato, mushroom, and so on. The common vacuum-fried fruits include pineapple, mango, guava, banana, apple, and so on. In addition, some companies have established a vacuum frying process for fish and shellfish. Nevertheless, these vacuum fryers are mostly applied for small-scale production (Moreira, 2014).

Vacuum fried products are usually prepared in small chunks or slices, and fried under much lower pressure than the atmospheric pressure of 101.325 kPa; the operating pressure of vacuum fryers is preferably below 6.65 kPa to significantly decrease the boiling point of water and fats in foods so that lower frying temperatures can be applied (Moreira et al., 1999; Dueik and Bouchon, 2011). The acrylamide formation and fat absorption of the fried products in vacuum fryers are also reported to be reduced significantly in comparison with the conventional types of atmospheric fryers (Granda et al., 2004).

Because the pressure is low during the frying process, the moisture and oil absorption of fried products is also reduced. Therefore, the advantages of vacuum fryers are not only to provide oil content reduction for fried products but also to maintain the oil quality under low temperatures. Furthermore, the fried foods are protected from quality loss in terms of flavors, natural color, and texture, because of the low frying temperature and the decrease in oxidation of fried products (Shyu et al., 1998; Garayo and Moreira, 2002). The latest innovations in vacuum fryers have produced models that can operate at a frying temperature below 90°C, thus avoiding the waste oil problem produced from the higher frying temperature of approximately 130°C in the previous generation of vacuum fryers (Dueik and Bouchon, 2011). Using electricity as an energy source is not recommended as a heating system in vacuum fryers because of their low-temperature applications.

A vacuum fryer contains five major components: (a) a vacuum pump; (b) a frying container; (c) a heating element; (d) a condenser; and (e) an oil-removal system. The vacuum pump is to evacuate the sealed frying container to reach the required pressure for the frying process and remove non-condensable gases. The frying container is a sealed vessel including a basket, a heating system, and a lid with a pressure gauge. A heating element can be of tubular or finned type, comprising nickel-chromium resistance wire that is spot-welded to a terminal pin. An electric or gas heating element is usually used in household or restaurant fryers with small capacity. A water or steam heating pump is used for continuous industrial fryers for large-scale production. A condenser is either a water-cooled or a refrigerated condenser to cool down the high-temperature vapor coming from the frying container during the frying process. The steam must be removed before reaching the vacuum pump to protect the pump from any vapor that could cause damage to the vacuum system by cavitation in the pump. The refrigerated condenser is designed to provide higher efficiency condensing than a water-cooled condenser. An oil-removal system is applied with the centrifugation method to spin the product-loaded basket at a high-speed rotation by a centrifuge motor connecting to a lift shaft, which can also adjust the basket position inside the frying container.

When heating the oil in the frying container to the required temperature, the raw material is placed in the basket but it is still suspended above the heated oil by controlling a lift shaft or rod. The frying container is sealed with a lid and the product-loaded basket is not sunk into the hot oil until the frying container reaches desirable pressure at approximately 1.33 kPa for initiating the flying process. According to the requirements of different fried products and frying oils, monitoring the level of pressure, moisture, time, and temperature accurately is a crucial step. When all of the parameters reach a favorable level, the product is lifted from the hot oil, and oil removal method is applied by centrifugation at the required speed and time. Finally, the fried product is removed from the frying container by opening the lid with pressurization. In some cases, the final fried product is also centrifuged by separate equipment or just suspended inside the frying vessel to get rid of the excessive oil on the surface of products. Finally, the vacuum-fried products are placed on absorbent materials, cooled down, and packed in suitable modified atmosphere packaging with nitrogen.

Vacuum fryers can be categorized into industrial-, pilot-, and laboratory-scale, based on their size. Because of process requirements, there are also batch and continuous types of frying equipment. The batch type of fryer is used for testing in laboratories or for small-scale production in pilot and processing plants. Conversely, the continuous type of fryer is used for large-scale production in food industries, mostly for the production of fruit and vegetable crisps in recent years. A variety of vacuum frying equipment can be designed and constructed according to the customer's requirements. A variety of vacuum fryers have been patented for different industrial purposes (Andrés-Bello et al., 2011).

A vacuum fryer with a 20 L camber capacity was used for frying slices of Chinese purple yam. The frozen yam slices were fried with vacuum pressure 90 kPa at 100°C for 15 min. Then the yam crisps were centrifuged at 450 rpm under the same vacuum pressure in the frying camber for 5 min to drain the frying oil from the surface of products. Finally, the fried yam crisps were removed from the fryer, cooled down, and packed in foil-film bags (Fang et al., 2011).

Gros Michel banana was fried in a well-designed vacuum fryer including a liquid ring vacuum pump, a condenser, a frying vessel, and a centrifuge. The frying vessel, containing a gas-heating system, was built with stainless steel composed of a 300 mm height, a 400 mm diameter, and a 6 mm thick wall. The lid of the frying vessel consisted of 8 mm thick stainless steel. The stainless steel condenser comprised a 9425 mm long tube of 19 mm internal diameter coiled inside the chamber with water-cooled circulation. After the bananas were peeled and cut into 4 mm thick and 25 to 30 mm cross-section diameter slices, they were fried in 13.7 L of soybean oil under vacuum pressure 8.0 kPa and at 100, 110, and 120°C for 20 min. After frying, the products were centrifuged at 450 rpm for 5 min to get rid of the excess oil from the surface of banana slices to decrease oil absorption (Yamsaengsung et al., 2011).

GASTROVAC vacuum frying equipment was designed and constructed under patent at the Polytechnic University of Valencia (Martínez-Monzó et al., 2004). It was used for frying sea bream fillets. This equipment contained a membrane vacuum pump, a pressure chamber with an inner basket, and a heating system with a temperature detector. The fillets were placed in 2 L sunflower oil and the ratio of fillet and oil ratio was approximately 0.07 w/w. Frying procedures were comprised of initial heating the oil to target temperature 30 min before frying, a depressurization before the fillet-loaded basket was submerged under the oil, the oil immersion of the basket while the temperature and vacuum reached the required values, a frying period of 10 min, and opening the lid after pressurization. The samples were fried at 90°C with 15 kPa, 100°C with 20 kPa, and 110°C with 25 kPa, respectively. However, the fried fillets were dried with paper towels after taking out from the frying chamber because this equipment had no oil removal mechanism (Da Silva and Moreira, 2008; Andrés-Bello et al., 2010).

There is a variety of different commercial vacuum fryers designed and constructed by many companies all over the world. A Taiwanese company, I-TUNG machinery industry, designs and produces three types of commercial batch vacuum fryers: Pilot-type, TWIN-5, and TWIN-100. These stainless steel fryers are designed for frying 25 to 100 kg potato, sweet potato, and taro crisps per hour and 10 to 50 kg fruit/vegetable crisps under 1.33 kPa of vacuum pressure (I-Tung Machinery Industry Co., Ltd, 2020). There is a cryogenic vacuum fryer designed to dry-fried products rapidly in a short time after the frying process to lower the oil content in the final product. It contains an electrical heating system and 50 kg capacity for each batch. The food range of the vacuum fryer includes fruits, vegetables, meats, and fish products (America TCA Machinery Inc, 2019).

10.3.3 Air fryers

Air frying, on the other hand, is the current modern alternative to deep-frying, using a small amount of oil and hot air in the closed compartment of an automated fryer. Due to health-related issues, like the amount of fat or oil, or levels of acrylamide in deep-fried products, air fryers were developed as alternatives to deep fryers (Zaghi et al., 2019). Unlike deep fryers, where oil does the cooking, air fryers use hot air, like convection ovens. However, unlike cooking in convection ovens, air frying is done in a small, compact, closed compartment, which heats up faster, gets hotter, gives off less heat to the surroundings, and moves air faster, resulting in a quicker and crispier final product (Paster, 2019; Pitre, 2019).

Air fryers are equipped with heaters and fans designed to circulate hot air evenly at high speeds through the products, providing a high level of heat transfer and, with a little bit of added oil, give a crispy product similar to deep-frying. Depending on the fryer model, heaters might be separate from the frying compartment, leaving only hot air for cooking, or directly heat the frying compartment together with the hot airflow. Hot air enters the frying compartment either from below, from one side (Fig. 10.11), or from both below and sides and is pulled upward by the fan, thus evenly heating the frying compartment (Zeb, 2019; Ubert Gastrotechnik GMBH, 2020). Additionally, some air fryers are also designed to first cook the products with steam and then with hot air (Ubert Gastrotechnik GMBH, 2020; Posner, 2020).

Currently, air fryers are more commonly used in domestic and commercial settings. Although domestic air fryers might have different styles, like paddle, basket, and countertop oven types, the common commercial air fryer style is the basket type (Fig. 10.11). Paddle-type air fryers include a stirrer in the middle of the frying pan, which moves in a circular motion throughout the frying process and eliminates food build-up, enabling the products to be evenly fried. In this case, the airflow is directed so that the hot air will circulate inside the pan (Peterson and Shaw, 2020; Review GiG, 2020).

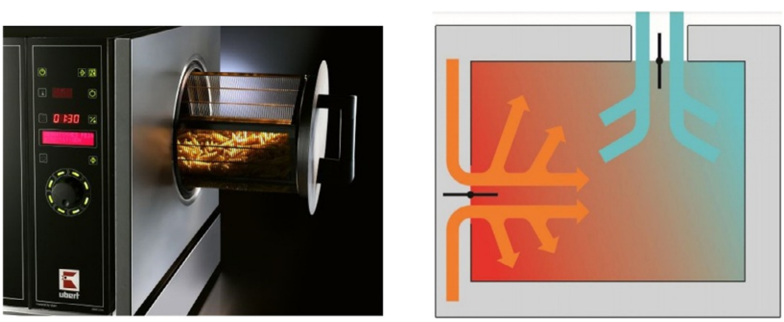


Fig. 10.11 Commercial air fryer with a cylindrical basket *(left)* and its airflow during air frying *(right)*.
Courtesy of Ubert Gastrotechnik GMBH, Raesfeld, Germany.

The basket-type air fryer includes a basket where the food items are placed, which is then inserted in the fryer. One side of the basket typically works as a door to close the frying compartment. Unlike the paddle type, where food is automatically moved, some basket-type air fryers might require taking the basket out and manually shaking it for even frying. The basket is perforated either from the bottom or from both bottom and sides, to allow excess oil drainage and airflow. Either the food and fat or oil is mixed beforehand or the frying basket is lightly greased with oil. Depending on the fryer model, the amounts of necessary oil or fat vary.

To get even product quality throughout the batch, which is especially important for commercial settings, food should be evenly distributed in the basket before frying. Some commercial models include a cylindrical basket, which could be completely filled and rotates during the frying process, ensuring even frying (Fig. 10.11). At the end of the process, the frying basket is removed and emptied by the operator manually or the products are poured out automatically by the air fryer to a tray beside it (Ubert Gastrotechnik GMBH, 2020; Quik 'n'Crispy Greasless Fryer, 2020). Although the frying process might take longer compared to typical deep-frying of French fries, it does offer a potentially healthier alternative (Zaghi et al., 2019; Zeb, 2019; Santos et al., 2017).

10.3.4 Microwave fryer

The microwave application for food production has developed gradually since 1990 and is considered to be an innovative method to improve food quality in a variety of processes including drying, thawing, baking, and frying. The use of microwaves in the food industry provides three major advantages: high energy efficiency, high food quality, and short processing time.

The multiphysics phenomenon of microwave heating can be described as heat transfer between food materials by electromagnetic radiation. When food materials absorb the microwave energy, it can be used to generate heat based on dipolar and ionic mechanisms. The common dipolar molecules in foods are water molecules resulting in dielectric heating. When the oscillation of water molecules in the electromagnetic field occurs, the polarized dipolar water molecules tend to realign with the direction of the field. Because of the high frequency of electromagnetic field provided by microwaves, the realignment and rotation of dipolar water molecules occurs at a million times per second, causing them to collide with other molecules with high internal friction. The motion and kinetic energy generated is tremendous, leading to the heating of food materials.

On the other hand, the ionic conduction mechanism also plays a critical role in microwave heating due to the oscillations and pattern formation of ionic migration in foods. Positive ions move on the direction of the electromagnetic field and negative ions move opposite to the direction of the field. The high-frequency shifting of the field direction brings about the high frequency of ion locomotion oscillating back and forth to generate heat in food materials by the collision and internal friction of molecules (Datta and Davidson, 2000; Sumnu and Sahin, 2008; Chandrasekaran et al., 2013). Modern microwave ovens usually offer oscillation of electromagnetic waves at a frequency of 2.45 GHz. Therefore, microwave heating and its heat transfer can be significantly influenced by the dielectric properties of the food materials and the depth of penetration.

Microwave frying is a new type of application in food production. In addition to the heat of its own frying oil, it can heat up and cook the fried materials from the outside to the inside, and also the energy from the microwave can be used as a second source of heating to quickly cook the fried materials from the inside to the outside because of the dipolar and ionic mechanisms of water molecules. This leads to a short frying time. In contrast with microwave frying, conventional open deep-frying provides a single heat source only from the hot oil to fried foods through the food surface by heat conduction. As a result, the application of microwave fryers is a great alternative to conventional fryers.

The evaporation rate of microwave frying is higher than conventional frying because the oscillation of electromagnetic waves increases moisture loss from fried products. The pressure on the food surface increases quickly and then pressure declines after moisture loss from the surface. Even though the surface pressure is only around 1.0 kPa, it affects the evaporation significantly under convective heat transfer (Datta, 2007). Microwave frying creates a pressure-driven flow to enhance water vaporization, resulting in higher oil absorption in comparison with conventional deep-frying during the same processing period (Feng and Tang, 1998). However, there is less processing time in microwave frying than in conventional frying, which may result in lower moisture loss and less oil absorption due to short frying time. Although the microwave fryer may cause high moisture loss in fried products, this disadvantage can be overlooked due to less frying time. (Oztop et al., 2007).

The domestic microwave oven can be used as a microwave fryer. The microwave frying of potato slices was studied under three power levels of 400 W, 550 W, and 700 W, over 2.0, 2.5, and 3.0 min of frying time. Three types of oil were used including sunflower, corn, and hazelnut oil. Microwave frying was operated in a commercial microwave oven to heat up 0.4 L oil in a glass container to 170°C before seven pieces of potato were fried in hot oil at the desired power level for a specified frying time (Oztop et al., 2007). A microwave fryer was used to fry frozen fish nuggets at 180°C for 3.5 min to compare with conventional deep-fat frying at the same temperature for 5 min. The microwave deep-fat fryer was manufactured by Chin Ying Fa Mechanical Industry Co., Ltd., Taiwan. It had $397 \times 397 \times 360$ mm interior dimensions and $610 \times 510 \times 630$ mm exterior dimensions. It was operated at 2500 W for microwave input and electric power of 2400 W for heating oil. However, the crust qualities of fish nuggets indicated no significant difference between the methods of conventional deep-fat frying and microwave frying (Chen et al., 2009).

The main components of the recently developed microwave fryer are a microwave generator, a frying tray, an oil sprayer, a heating layer, a partition plate, and a cover plate. Raw materials are placed evenly in the frying tray and then this tray is put into the heating layer. The fried oil is sprayed on the raw material surface with the sprayer. The electrical power supply of the microwave generator can provide approximately 4000 v for the magnetron, which is a high-powered vacuum tube, to produce selfexcited microwaves by high-frequency oscillation. There is a rotatable agitator with metal fans in the frying chamber to reflect and distribute microwave energy homogeneously for frying products evenly (Tang, 2013).

Most microwave fryers are modified by equipping a microwave generator on conventional deep fat fryers. A deep-frying apparatus is applied with microwave energy from separate magnetrons to a pair of ceramic vessels placed side by side. The magnetron is not in an energized state until the lid of the frying vessel is completely closed to push down a plunger switch (Thomas, 1986). However, the microwave fryer has developed rapidly to produce a user-friendly design that is simple and easy to control. A microwave fryer contains a magnetron, an oil vessel, a detachable frying container, a lifting mechanism to move the frying container and the oil vessel, a temperature monitor, a device protection system, and an oil amount detector (Andoh et al., 1996). A microwave generator device is equipped in a frying chamber in a closed container. During the frying process, the container rotates around with an inclined axis of 20 to 45 degrees at a speed of 1 to 100 rpm (Vandenbussche, 2009).

A combined batch microwave/frying appliance was invented in Taiwan (Cheng and Peng, 2006). It contains a frying device, a microwave generator, and a supporting component. The frying device includes a housing containing an oil groove in the upper end with an upward opening. The Mesh is installed in the oil groove so that fried food items can be placed there. Besides, the gas stove uses a number of heat tubes to heat oil in order to provide heat. The microwave generator comprising the magnetron and the waveguide is equipped in the top lid of the frying device. When raw materials are fried in hot oil in the oil groove, the microwave also directly heats the materials from the top. The products can be fried evenly on the food surface and also internally to avoid the risk of burnt food surface and undercooked interior of final products. Because of providing short processing time, crispy and crunchy fried products can be obtained. The supporting component is located between the microwave generator in the lid and the container of the frying device; these components including two telescopic pneumatic rods, which support the body of the microwave generator in the lid when the frying device is in the open position.

There is a continuous microwave hybrid fryer developed by Tsung Hsing Food Machinery in Taiwan (Tsung Hsing Food Machinery Co., Ltd, 2020). A microwave launch cavity and a microwave transmitter are equipped above the middle section of the oil-frying tank. The microwave, as the second heating source, can achieve the processing optimization of the fried products by configuring the microwave emission power. There is a microwave anti-leakage design at the inlet and outlet to prevent operators from any microwave exposure. A clean-in-place automatic cleaning system is equipped in the frying tank, the heating pipes, and the inner frying hood. A pressure protection system is installed in the oil circulation tube to prevent the pump from idling or oil-free ignition. There are other features including overheating protection in exhaust gas, an automatic temperature controller, and an emergency stop system.

10.4 Fryer selection

To select the most appropriate fryer for the desired final products is very important in the frying industry. In order to attract the purchasing preference of customers, producers need to improve their final fried products for all sensory attributes including appearance, texture, aroma, flavor, and mouth-feel. Furthermore, in order to lower the manufacturing cost, producers also need to understand the factors that affect the frying process. However, it may occur to some manufacturers unfamiliar with industrial frying that just one single type of fryer can be used for frying a variety of foods. Actually, the characteristics of raw materials, their sensory qualities, the frying operation, and processing designs all have to be considered when deciding on a frying system. In Fig. 10.12, the frying line for Indian snacks of moong dal is a typical industrial continuous fryer. It includes feeder, heater, oil circulation pump, oil tank, continuous fryer, cooling conveyor, and flavor applicator.

Many factors should be considered in choosing an appropriate fryer for the specific requirements of a food business (Gupta, 2004; Gupta et al., 2004); these include:

- The physical and chemical property of food materials
- The desired sensory attributes in the final fried product
- Productive capacity
- Oil turnover rate
- Oil filtration
- Heat load
- Heating system
- Pollution control
- Fryer maintenance and sanitation

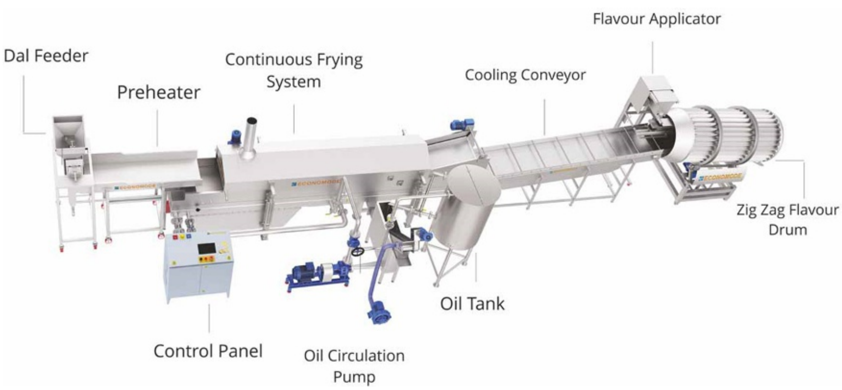


Fig. 10.12 Moong dal frying line.
Courtesy of Economode Food Equipment India Pvt. Ltd., Maharashtra, India.

10.4.1 The physical and chemical properties of food materials

Different types of fried products made from different raw materials have different physical and chemical properties. Batter and breaded coating products have a more complicated process design than uncoated products such as meatballs, potato fries, and vegetable chips. The design of conveyor belts in fryers should be based on the density of fried products. The buoyancy of fried products results in floating, sinking, or submerging in hot oil. Some food materials even change their buoyancy during the frying process. In addition, the chemical components of food materials also influence the fryer design. When the raw materials have high water content, the dehydration and emission of the fryer have to be considered.

10.4.2 The desired sensory attributes in the final fried product

The sensory attributes include color, shape, size, texture, flavor, and aroma of final products. The frying method and the process plan affect these attributes significantly. A variety of optical analyses can be used for color measurement of fried foods (Lee et al., 2020). The color of vacuum-fried mango slices was lighter than atmospheric frying (Da Silva and Moreira, 2008). Mango chips with atmospheric frying had less carotenoid retention compared to vacuum frying (Nunes and Moreira, 2009). The special feed belt and product-resting zone also need to be designed based on product characteristics.

10.4.3 Productive capacity

The productive capacity represents the maximum output that can be achieved by a processing line or equipment. The desirable productivity of the food industry affects the selection of fryer types. The fryer capacity is usually expressed as a certain figure in weight or volume per hour or per minute, such as in lb/h or kg/min. The floor type or industrial continuous type of fryer has higher productive capacity in comparison with the countertop type or batch type of fryer. The area of the processing plant or operation zone determines the physical dimensions of the fryer, the conveyor length and width, and the loading rate. In addition, there are other factors such as operation time of the fryer, the required frying time for a high quality of final products, and the facility of storage and distribution. All of them are taken into account to choose an appropriate productive capacity in food manufacturing.

10.4.4 Oil turnover rate

The definition of oil turnover rate is the time (in hours) required for the total oil absorption of fried products from a whole oil content during the entire frying process. The theoretical oil turnover rate can be calculated as:

$$\begin{array}{c}\text{Theoretical}\\ \text{oil turnover rate(h)}\end{array} = \frac{\text{The weight of total oil capacity in frying process(kg of lb)}}{\text{The weight of oil absorption by fried materials per hour(kg or lb/h)}}$$

The above calculation exhibits a 100% capacity frying operation. Nevertheless, fryer utilization is reduced to 80%–90% in reality. So the actual oil turnover rate would be calculated as:

$$\text{Actual oil turnover rate (h)} = \text{Theoretical oil turnover rate (h)}/0.8 \text{ or } 0.9$$

Nowadays, a fryer that requires large volumes of oils costs enormously to operate. A low oil volume in a fryer guarantees a low oil turnover rate. When the oil turnover rate decreases, the deterioration and rancidity of fried oil can be reduced to improve the end-product quality. The oil turnover rate of the fryer should be sustained in the 5 to 12 h range for the maintenance of fried oil quality (Dunford, 2003).

10.4.5 Oil filtration

During the frying process, food debris is produced and then remains within the fried oil resulting in oil degradation and causing undesirable flavor in the final fried products. Therefore, the purpose of the oil filtration system is to remove fines from fried oil periodically to maintain oil quality at a certain level. The combination of a centrifugal and a motorized filter is commonly applied to remove and treat approximately 5% of fried oil. The selection of the type of oil filter depends on the amount, the size, and the texture of the food particles required to be removed. For example, battered and breaded products usually deposit huge amounts of debris in oil so that bottom-dredging needs to be applied. Furthermore, there should not be a significant quantity of oil loss. Besides, the oil quality should not deteriorate throughout the oil filtering process, similar to the downsides of paper filters.

10.4.6 Heat load

Heat load requirement depends on frying various products. Potato chips and corn chips typically require more heat energy than other coated fried products in the frying system. The mass and the energy of heat transfer have to be calculated accordingly, including all heat transfer and loss in the frying chamber, pipes, tubes, exhausts, and filters. The important factors of the delta-T (ΔT) along a whole fryer and temperature recovery time have to be considered for heat load calculation. ΔT is defined as the difference in the gradient of the temperature difference between the feed of raw materials (inlet) and the discharge of final fried products (outlet).

10.4.7 Heating system

There are two types of oil-heating systems: direct heating systems and indirect heating systems. A direct heating system uses electrical heating elements or burner tubes to heat up the frying oil in the frying vessel directly. Because the heating elements are submerged in and contact the frying oil directly, the heat energy is transferred into the fried oil completely through the currents of natural convection. A direct heating system is commonly applied for small-scale production in batch frying in the restaurant or household. An indirect oil-heating system is normally applied by large industrial continuous frying plants. The oil is heated in a heat exchanger with an external thermal fluid like a broiler or a heater by electricity or gas. The design of these heat exchangers is commonly of cross-counter flow type and these external thermal fluids can be chlorinated hydrocarbons or water vapor (Wu et al., 2013).

10.4.8 Pollution control

All types of fryers, especially continuous industrial fryers, can release certain (sometimes large) amounts of odor, steam, gases, and volatile chemical compounds to the surroundings. According to the local regulations and policies in different cities and countries, scrubber systems are required to be equipped on the fryer compulsorily. A scrubber system uses liquid to remove undesirable pollutants from a gas stream to achieve the purpose of environmental pollution prevention.

10.4.9 Fryer maintenance and sanitation

A comprehensive management program for fryer operation should be established to improve the fryer efficiency and minimize any errors and mistakes during the frying process. The start-up and shut-down of frying equipment do more damage to devices than the period of processing. The hardness of water used in food processing plants also affects the effectiveness of cleaning and sanitation (Lee et al., 2015). Heat control for oil loading and circulation needs to be well-programmed to avoid the fryer operating in the idle mode. Austenitic stainless steel should be used for the construction materials on the contact surface instead of copper and brass, because these enhance oil rancidity. Sanitation procedures should include a CIP (clean-in-place) system following the general provisions such as good manufacturing practice (GMP) and hazard analysis and critical control points (HACCP). Pathogens can attach to different kinds of organic and inorganic materials on the surface to develop biofilms; this not only increases the risk of foodborne outbreaks but also reduces the apparatus efficiency. Chlorine solution is widely used in facility sanitation (Lee et al., 2016). All welding joints should be intact, not rough, and all pipes and tubes should be cleaned regularly.

10.5 Industrial fryer

Frying technology has improved and evolved enormously for a century and the conventional frying methods such as deep-fat frying in the kitchen are no longer sufficient for the current demands of consumers. The requirements of a fryer in the modern food business include efficient process, rapid production, simple and safe operation, high-quality products, and low cost. Most consumers desire low-oil content, high quality, and convenient fried products to achieve a healthy lifestyle. The frying oils and solid fats used in frying procedures may cause adverse effects such as a high amounts of trans fats and saturated fatty acids. Alternatives to frying oil such as the oleogel can be used during frying processes (Demirci et al., 2020). The industrial frying operation has become a large-scale process and it can produce thousands of kilograms of products hourly. Unlike a fryer used in restaurants or food services, the process of industrial fryers is highly complicated to allow all manufacturing steps following precise requirements automatically or sometimes semi-automatically.

Any kind of food materials can be fried, including coated or uncoated forms. There are various industrially produced fried products in the market, as listed below:

- Plain or seasoned chips: potato chips, corn chips, tortilla chips, vegetable chips, and fruit chips.
- Fried meat, poultry, and seafood products: chicken-fried steaks, batter-coated chicken, batter-coated fish fillet, and batter-coated shrimp.
- Fried nuts: seasoned or sweet peanut, pecan, cashew, pistachio, walnut, hazelnut, and so on.
- Par-fried products: French fries, cheese, vegetables, chicken/fish nuggets or patties.
- Extruded corn products.
- Fabricated products.

10.5.1 Types of industrial fryers

In the frying industry, there are two types of fryers: the batch type and the continuous type. Batch fryers are used for small-scale production in the restaurant, catering, and other food services. Continuous fryers are applied in food manufacturing and processing plants for mass production.

10.5.1.1 The batch fryer

The batch fryer was described in the previous sections when the frying systems in the restaurant and food services industries were discussed. Countertop frying kettles (Figs. 10.3 and 10.4) are commonly used. The commercial deep fryer can be classified into four categories: flat-bottom fryers (Fig. 10.1), tube-type fryers (Fig. 10.6), open-pot fryers (Fig. 10.7), and commercial pressure fryers (Fig. 10.10).

Flat-bottom fryers are used for frying dough such as Spanish churro and Middle Eastern falafel. The fried dough products can float in the top of fried oil freely to maintain the desired shape of the final products. Tube-type fryers are used for bread-coated products such as onion rings and cheese sticks because these fryers contain large cold zones to prevent all remaining food particles from deteriorating fried oil in order to maintain the oil quality. Open-pot fryers are usually applied for French fries and hash browns because their V-shaped frying vessels can decrease the usage of oil. Commercial pressure fryers are used for frying bread-coated products like fried chicken because high pressure enhances the oil heating system and maintains the fried chicken quality (KaTom Restaurant Supply, Inc, 2020).

10.5.1.2 The continuous fryer

The continuous fryer is operated in fried snacks processing plants rather than in restaurants or catering businesses because of the high volume of production required. There are various designs to fulfill different requirements from food manufacturers including the designs of a flat straight frying vessel, a U-shaped frying pan, and an automatic multi-zone fryer.

Fig. 10.13 Indirect heated fryer with the electrical heat exchanger.
Courtesy of GEA Group, Düsseldorf, Germany.

Raw materials are fed into one end of the fryer (inlet) and fried products are transported to the opposite end by conveyor systems. The fried oil is heated in a straight or U-shaped vessel under frying temperature control with a direct or indirect heating system (Fig. 10.13). An automatic multi-zone fryer is widely used because of the decent maintenance of fried oil quality. The oil is heated indirectly by an external heat exchanger and is then driven into different designated oil sections in the frying vessel (Fig. 10.14). However, this design of oil heating and capacity may retain fried oil at high temperature constantly and enhance oil turnover time, leading to increased oil oxidation and rapid deterioration.

Fig. 10.14 Multi-zone fryer.
Courtesy of GEA Group, Düsseldorf, Germany.

10.5.2 Components of an industrial frying process

An entire industrial frying process consists of a variety of devices and mechanisms. A semi-automatic production line of potato chips is a combination of batch and continuous processing arrangements (Fig. 10.15). It includes feeder with hopper, shaker, control panel heater, oil filter, oil tank, continuous fryer, inspector shaker, and flavor applicator. It is an economical operating line with optimal automation in which the major processes are automated, except for potato grading, peeling, and slicing.

Even though the fryer certainly plays the most crucial role in a whole frying system, many other peripheral and integral apparatuses and devices also integrate to facilitate and complete production. In Fig. 10.16, a fully automatic frying line of potato chips is shown. Its components are as listed below:

- Hopper with feeder: potatoes supplied at a controlled feed rate
- Grader: the removal of undesirable shape and size potatoes by grading and sorting
- De-stoner
- Peeler: potato peeling
- Inspection conveyor: visual inspection taking place
- Single potato feed conveyor
- Slicer: single potato slicing
- PLC control panel: a programmable logic controller (PLC) is used to control manufacturing processes by an industrial digital computer
- Washing station: potato slices washed before blanching
- Transfer conveyor
- Blanching system: scalding potato slices in steam or boiling water in a short time to inactivate enzymes within the potatoes and clean the surface of slices
- Air-sweep system: After blanching, nozzles release a large volume, high pressure burst of compressed air to dewater the potato slices.
- De-watering conveyor with air knife
- Vibro-shaker: extra water removal
- Continuous frying system: this has a variety of designs based on specific requirements, such as submerged conveyors and paddle wheels for potato chip fryers
- Oil receiving and storage system: oil pump recirculating and piping
- Oil heating system: direct and indirect heating system

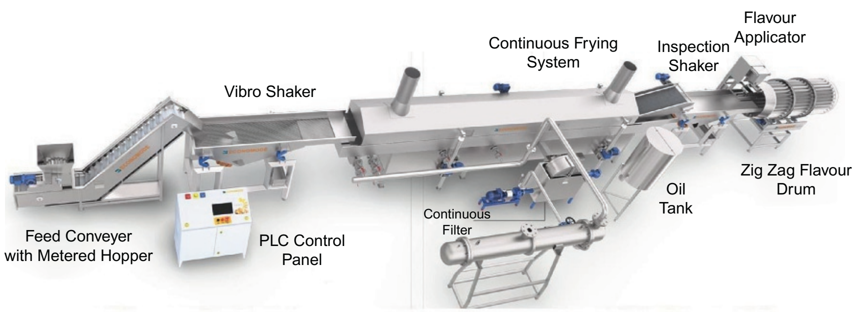


Fig. 10.15 A semi-automatic potato chips line.
Courtesy of Economode Food Equipment India Pvt. Ltd., Maharashtra, India.

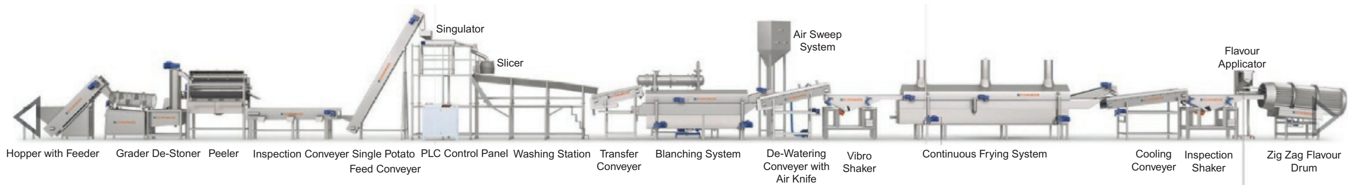


Fig. 10.16 A fully automatic potato chips line.
Courtesy of Economode Food Equipment India Pvt. Ltd., Maharashtra, India.

- Oil temperature and level monitors
- Oil filtration system: specifically designed conveyor may be equipped to dredge the bottom of fried oil for the removal of precipitated bulk particles or sludge, especially for coated products
- Cooling conveyor or equilibrator for cooling
- Inspection shaker: fried chips color monitoring with optical sorters
- Flavor applicator: salt and seasoning adding
- Zig-zag flavor drum: flavor mixing
- Extruder: fried products extrusion
- Filling/packaging machine: modified atmosphere packaging system applied with a nitrogen flush
- Metal detectors
- Fire-restraint controller
- Process alarm for fault detection and diagnosis in each process unit

10.6 Current innovations in fryers

Food producers in the frying industry make efforts to improve frying systems so that ideal processing conditions can be achieved, such as the life extension of fried oil, highly efficient manufacture, high-volume production, low-cost operation, low-energy requirement, and favorable fried products.

There are different advantages and disadvantages for the different frying systems. In Table 10.1, there are comparisons between different fryers in relation to various frying factors. Researchers and manufacturers seek to develop innovative frying technologies to invent new types of fryers that contain advantages from different fryers. For example, the microwave-assisted frying technology was reviewed in this chapter to indicate that this innovative technology can enhance energy-usage efficiency and the quality of the fried product (Ekezie et al., 2017). The microwave-assisted vacuum fryer was studied for the oil-uptake reduction and the quality improvement of fried potato chips. Microwave-assisted vacuum frying decreased oil absorption of fried potato chips in comparison with vacuum frying only. Furthermore, the microwave application also improved the color and crispness attributes of fried potato chips significantly. Under the observation of scanning electron microscopy, the integrity of the cell structure of fried chips was well-preserved after microwave-assisted vacuum frying (Su et al., 2016).

Ultrasound and microwave have also been studied in relation to a vacuum frying system. Purple-fleshed sweet potato was fried in a vacuum fryer with the assistance of ultrasound and microwave technology. The results exhibited that the combination of these technologies not only enhanced the moisture diffusivity and evaporation rate but also reduced oil absorption of fried potatoes compared to vacuum frying without the application of ultrasound and microwave. An improvement of the crispness and color in fried samples was also observed. The higher the power level of ultrasound and microwave is, the better is the quality of fried products produced (Su et al., 2018). The same combination of ultrasound and microwave technology was used in a vacuum

Table 10.1 A comparison of different types of fryers.

Fryer	Frying temperature	Frying pressure	Frying time	Oil oxidation	Common fried product	Oil uptake of fried products	Fried product characteristics	Production capacity	Energy efficiency	Operational costs
Pan fryer	High 180–200°C	Atmospheric pressure at 101 kPa	Long	High	All types of foods	High	Oxidized easily, may cause acrylamide formation	Low	Low	Low
Deep fryer	High 180–200°C	Atmospheric pressure at 101 kPa	Long	High	All types of foods, snacks	High	Oily, may cause acrylamide formation, high oxidation	High	Low	Medium
Pressure fryer	Medium 110–130°C	Additional 35 to 105 kPa pressure given	Short	High	Fried chicken, breaded shrimp/fish, vegetables, rice, pudding, custard	Low	The retention of intact flavor in the product	Medium	Medium	Medium
Vacuum fryer	Low below 90°C	Low below 7 kPa	Short	Low	Fruit and vegetable chips	Low	Low oxidation	Low	Medium	High
Air fryer	High heated air up to 200°C	Atmospheric pressure or additional pressure given	Short	Low	All types of foods	Low	High preservation of flavor and aroma	Low	Medium	Medium
Microwave fryer	Medium 160–180°C	Atmospheric pressure at 101 kPa	Short	Low	All types of foods	Variable	The highest quality	Low	High	High

fryer for button mushroom chips. The findings also showed that this frying-enhanced technology preserved the nutrition and quality of fried mushroom chips (Devi et al., 2018; Devi et al., 2019).

A pressure cooker is a common kitchen appliance in many households and air fryers have become popular in recent years. Therefore, a manufacturer developed a cooker/fryer combined countertop apparatus including a housing, a heater, a fan, a pressure pot, and an air fryer pot. The heater heats external air from outside and then the fan blows the hot air into the inner space of the air fryer pot (Itzkowitz, 2020). Another development of fryers is to have alternative frying platforms. This fryer contains a switchable mechanism of operation between a pressure fryer and an atmosphere open fryer. The selectively closeable frying vessel contains a cover with a locking device by rotation of a handle when an open frying vessel is used. A pressure assistance feature is also provided to reach a required pressure for small fried-loading when a pressure frying platform is used (Eros et al., 2018).

Countertop air fryers have become widely used and are designed as an indoor appliance. However, outdoor air frying apparatuses have been demanded by customers recently because of the advantage of air frying. Hence, an outdoor cooking appliance equipped with an air frying function has been developed (He et al., 2020). This gas air fryer comprises a cooking chamber, a heat exchanger, a blower, and a frying burner. Ceramic and infrared burners have been used in recent years to obtain more heat energy from the fuel and dispense heat energy more uniformly (Bendall, 1998). The frying burner is designed to combust fuel for creating heat and then the blower is adapted to circulate the heated airstream from the heat exchanger into the cooking chamber to fry food materials. This outdoor air fryer can be used in open areas like backyards or parks. It is also applied in catering businesses and any other outdoor food services.

The cool zone has become a popular additional design in the modern fryer. A cool zone is an extra space underneath the heating element at the bottom of the frying chamber into which food debris and chunks sink to be collected. Because the oil temperature is much lower in the cool zone than in the regular frying zone, the food particles are prevented from burning and oil quality can be maintained. Cool zones are usually equipped in huge floor-mounted continuous fryers but sometimes also in small batch fryers. A tube-type fryer contains a large cool zone because the tubes are installed above the bottom of the vessel to allow oil and food particles to cool down in a large space.

10.7 Conclusions and perspectives

Frying is one of the most traditional methods for food preparation in human history all over the world. Different regions developed various frying techniques based on their own indigenous ingredients and food culture. The geographical territory and local climate not only affect agricultural products but also influence consumer preference for fried products. In this chapter, we discussed the major types of fryers, including two types of conventional fryers and four types of alternative fryers. The development of frying technology always depends on the demands of food manufacturers and of customers. Some important elements were mentioned made for the improvement of the frying system two decades ago (Moreira et al., 1999). Even though many mechanical engineers have invented a variety of fryers over a century, there are still some crucial factors currently required to be considered in the future. They are listed as follows:

- The quality of fried products: This includes the reduction of fat content, the prevention of nutritional loss, and the improvement of sensory attributes. Thereby, the purchase desire of customers to fried products will be increased significantly.
- Frying process efficiency: Automatic systems are less labor-intensive and decrease human error during operation. Besides, the fryer design should focus on heat capacity and heat exchanging in order to save energy and reduce fuel costs.
- Oil control: Frying oil is the most crucial ingredient in frying production. Oil receiving and storage, oil circulation, oil heating, and oil filtration need to be designed based on the requirements to maintain oil quality.
- Emission control: In recent years, environmental protection and its related regulations have gradually become emphasized. The emission control of industrial fryers is of great concern nowadays. Emission control devices are applied to industrial frying systems for the removal or reduction of pollutants. Mist collectors, scrubbers, incinerators, air filters, catalytic converters, and electrostatic precipitators are all examples of technology for emission control purposes.
- Real-time online monitors: A monitoring system should be established for the whole frying process. The sensors can measure frying oil condition and fried product quality in real-time through online reporting. Alarm systems should be applied and corrective action taken when deviations occur unexpectedly during operation. Computer-based controllers are required to be programmed well.
- Combination systems: Two or more frying systems can be merged into one system under one single operation to develop innovative fryers.

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