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"Air impingement thawing for food service fried food"

Ph.D. Student
Arianna Bozzato

Supervisor
Lara Manzocco

Co-supervisor
Emidio Tiberi

In collaboration with

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"Scongelamento ad *air impingement* per alimenti fritti nella ristorazione"

Dottorando
Arianna Bozzato

Supervisore
Lara Manzocco

Co-supervisore
Emidio Tiberi

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Preface

This project was carried out within The Research Hub™ by Electrolux Professional. This is a research centre where students work with company researchers, engineers and chefs for their bachelor, master and PhD thesis or on other research projects cofounded by other research centres. The multidisciplinary nature of the team allows to investigate research topics, regarding food service and laundry service, from different points of view and to build new knowledge based on the results of a network of interconnected researches. This work, accordingly, is included in the food service context and stems from a strict collaboration with other students. In this project, thermal simulations, mechanical feasibility studies and mathematical optimization techniques were implemented alongside the study of food processing implications, with the scope of performing an evaluation of a novel thawing method for professional food service.

Summary

Long thawing time associated to conventional refrigerator method is responsible for scarce responsiveness of food service thawing process to fluctuations in daily customers number. This results in food losses and indirectly in costs for space requirements; these issues are especially critical for quick service restaurants. Air impingement, exploiting high-speed impact of heated atmospheric air onto products surface, has been successfully used to reduce thawing time of food simulants, but to date scarce information about its effect on food is available. Aim of this doctoral thesis was to test the suitability of air impingement method as an alternative for food service thawing. This thesis first examined the effects of thawing on meat structure and their predicted consequences on frying performances. Successively, ideal requirements for a food service thawing method were identified. In a second stage, an air impingement prototype for thawing was developed. Frozen bags of chicken fingers, commonly thawed in quick service restaurants before frying, were chosen as study case. Combinations of thawing parameters, to be set in the air impingement thawing prototype, were thus optimized for chicken fingers. After application of the identified thawing cycles, structural modifications of the chicken fingers and their consequences on the quality of fried products were evaluated. These results were compared to those of refrigerator or microwave thawed samples. Finally, air impingement thawing versatility was evaluated on different food products. The results of the project demonstrate that air impingement thawing is well suited to noticeably reduce thawing time of the considered food service products and to address the identified requirements for food service thawing. Moreover, the performances of air impingement thawed animal products were reported for the first time. Application of this thawing method in field is currently studied in The Research Hub™ by Electrolux Professional. The focus will be on the processing implications of an industrialized appliance, which could not be evaluated on the prototypal application developed in this thesis.

Sommario

I lunghi tempi associati allo scongelamento refrigerato ne limitano l'adattabilità alle fluttuazioni del numero di clienti nella ristorazione. Questo provoca perdite alimentari, in aggiunta a costi per gli spazi necessari al processo; problematiche critiche per i *quick service restaurants*. L'*air impingement*, che sfrutta l'impatto ad alta velocità di aria atmosferica sulla superficie dei prodotti, è stato impiegato con successo per ridurre i tempi di scongelamento di simulanti alimentari, tuttavia scarse informazioni sono disponibili sul suo effetto sugli alimenti. Lo scopo di questa tesi di dottorato era testare l'idoneità del metodo *air impingement* per lo scongelamento nella ristorazione. Nella prima parte di questa tesi, sono stati esaminati gli effetti strutturali dello scongelamento sulla carne e le relative conseguenze previste sulle prestazioni in frittura. Successivamente, sono stati identificati i requisisti per l'applicazione nella ristorazione. Nella seconda parte, è stato sviluppato un prototipo per lo scongelamento ad *air impingement*. *Chicken fingers* imbustati, comunemente scongelati per essere fritti nei *quick service restaurants*, sono stati selezionati come caso studio. I parametri di processo da impostare sul prototipo sono stati dunque ottimizzati per i *chicken fingers*. Successivamente all'applicazione dei cicli di scongelamento, sono state analizzate le modificazioni strutturali dei *chicken fingers* e la qualità del prodotto fritto. I risultati sono stati comparati con quelli di campioni scongelati in frigorifero o microonde. Infine, la versatilità del metodo *air impingement* è stata valutata su diversi prodotti alimentari. I risultati di questo progetto dimostrano che l'*air impingement* riduce notevolmente i tempi di scongelamento dei prodotti considerati e risponde ai requisiti per lo scongelamento nella ristorazione. Inoltre, per la prima volta sono state riportate le prestazioni di alimenti di origine animale scongelati con *air impingement*. Alcune implicazioni di processo che non potevano essere valutare sulla versione prototipale sviluppata in questa tesi, sono attualmente allo studio in The Research Hub™ by Electrolux Professional.

Chapter 1 State of art

In this chapter, quick service restaurants (QSR) characteristics and competitivity factors were described. Production steps of one of their typical food preparations - fried chicken fingers - were analysed to identify opportunities of improvement. The criticisms of thawing process, conventionally performed in refrigerators or cold rooms, were discussed in term of time/space requirements and food loss generation. In order to identify a promising alternative to conventional refrigerator thawing for QSR, motivations for thawing meat, its effect on meat quality and possible effects on final fried products were analysed. Successively, the requirements for a QSR thawing method were defined. Accordingly, traditional and alternative thawing methods were considered. As a consequence, air impingement technology and available data about its application for thawing were described in detail.

1.1 Quick service restaurants (QSR)

Over the past decades, consumption of Food Away From Home (FAFH) has increased in high-income and urban societies, even exceeding food at home expenses in the USA (Janssen, Davies, Richardson, & Stevenson, 2017; Saksena et al., 2018). Therefore, attention to food service - the business of making, preserving and dispensing prepared foods - has grown, with the aim of optimizing its processes and matching the needs of operators and customers. Several segments of food service establishments can be identified considering service level, food quality, variety and price. Restaurants are the major source of FAFH, but other outlets may offer food as hotels, schools, retail stores, catering events, and vending machines. Saksena et al., (2018) identified two main types of restaurants: full service, with wait staff that continually tends to customers; and QSR - also known as fast food or limited service

- offering counter service but not wait staff. Globally, QSR income amounted to $873.4bn in 2017, representing 27.8% of the foodservice industry's aggregate value (Gallarza-Granizo, Ruiz-Molina, & Schlosser, 2020). Accounting for USA alone, in 2018, consumers spent $299bn in QSR (Richardson, Lefrid, Jahani, Munyon, & Rasoolimanesh, 2019). While, in 2015, roughly 54 % of the over 630,000 restaurants operating in the USA were QSR. Over 60 % of those were chains, namely brand of restaurants that operate 20 or more outlets (Saksena et al., 2018). QSR chains expanded in the 1950s and are characterized by a relatively limited menu of low-cost, quickly served, and predictable food. They exploit a franchise model where local restaurant owners are licensed to use chain's common building design, food, and delivery theme (Saksena et al., 2018). Also, production steps in QSR are standardized to ensure the safety of products and consistency of food quality. QSR buildings (Fig. 1) are characterized by a food service counter - recently partly substituted by kiosks - where customers interact with food service operators, and a kitchen. The latter is divided in areas for receiving/storage of ingredients (divided in room temperature, frozen and chilled storage areas), food preparation, cooking/hot preservation and a separated cleaning area.

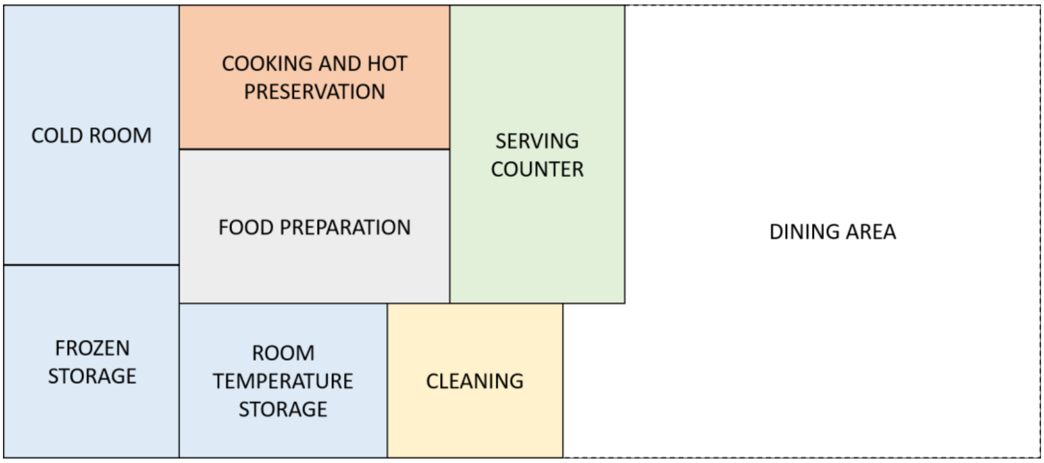


Fig. 1 Schematic representation of quick service restaurant areas.

QSR have to cope with high competition (Ketana, 2014; Mathe-Soulek, Slevitch & Dallinger, 2015) and many other challenges, including alienation and quick turn over of staff (DiPietro & Pizam, 2008), increased attention of guests to sustainability and green practices not balanced by willingness to pay more (DiPietro, 2017), and growth of interest regarding food safety and healthfulness of menu items. The latter was originated by FAFH generally containing more saturated fats and sodium, and less calcium, iron, and fiber than food at home (Saksena et al., 2018). In particular, excessive intake of calories and saturated fatty acid is of public concern due to its correlation with many diseases common in developed countries, such as obesity and coronary heart disease (Miranda et al., 2010). Although QSR have not been linked directly to obesity-related illness, they added in their product portfolio low-carb, zero-grams-of-trans-fat and low-fat products alternatives (DiPietro, Roseman, & Ashley, 2004; Ottenbacher & Harrington, 2009; DiPietro, 2017). Furthermore, U.S. Department of Health and Human Services' Food and Drug Administration (FDA) created menu label regulations that require chain restaurants to make calorie information publicly available (Saksena et al., 2018). In addition, to achieve efficiency and to withstand increasing scrutiny over their food management practices, QSR need to adopt strategies to reduce food wastes (Martin-Rios, Demen-Meier, Gössling, & Cornuz, 2018). In particular, losses of raw materials as well as wastes of ready-to-consume products occurring in the kitchen (Aytaç, K., & Korçak, 2021). In fact, total food wastes in food service industry were estimated 18% of the food input, of which 13.5% possibly avoidable (Beretta, Stoessel, Baier, & Hellweg, 2013). Moreover, only in United States, a total food waste of 2.12M Tons (19.7% of food service wastes) was calculated for limited service restaurants in 2019 (Refed, 2021).

To increase competitiveness in food service, it is not only essential to reduce costs, but also to create perceivable value for customers. The latter is expressed as willingness to return to the restaurant and to recommend it. Main success factors identified for QSR are food quality and convenience, aided to a lesser extent by service quality and restaurant environment (DiPietro, 2017; Richardson et al., 2019). Convenience, in this context, has been defined as the degree to which a consumer saves time and energy eating at a restaurant compared to home preparation of meals (Richardson et al., 2019). For these reasons, QSR are focused on the optimization of food production times and the minimization of customer wait times. Strategies as addition of information on menu to distract guests may be used (DiPietro, 2017), but beneficial results often derive from the use of technology. This may be in the form of a more efficient system to control operations as inventory and reservation (DiPietro, 2017), or more advanced kitchen appliances. These in fact are fundamental in enabling operators to obtain more easily a consistent food quality and to control more efficiently utility, food and labour costs (Ottenbacher & Harrington, 2009; Rodgers 2007, 2008; DiPietro, 2017). The development of advantageous food service appliances hence has to focus on operators' needs. Detailed knowledge of QSR production lines and critical points is needed to identify opportunities for time-savings and to limit the waste of resources, to ultimately improve restaurants competitiveness and customers satisfaction.

1.2 Study case of a QSR production line: fried chicken fingers

Poultry meat recorded one the highest growth rates of animal products over the last decades, reaching 28% of global meat sector in 2015, and is further expected to grow by OECED-FAO experts (Augustyǹska-Prejsnar, Ormian, & Sokołowicz, 2018; Petracci & Berri, 2017). Chicken is the most cost-effective commercially produced meat in the world and the most widely consumed thanks to its healthy reputation, simple handling and fewer religious barriers (Petracci & Berri, 2017; Vissers, de Jong, van Horne & Saatkamp, 2019). From a nutritional perspective, lean chicken meat has high protein content and contains less fat, trans-fats and cholesterol compared to red meat, lowering the risk of coronary cardiovascular disease. In QSR, poultry products come in a wide variety. Examples are grilled chicken breast, Caesar salads, or fried products as chicken fingers, chicken wings and nuggets. In particular, chicken fingers are a popular and global product that can be considered a representative study case of QSR products. Fig. 2 portrays the typical production steps of fried chicken fingers inside QSR, the appliances typically used for each step, step durations and the critical steps where food loss and food waste mainly occur.

Responsabile del procedimento: dott. Nome Cognome - nome.cognome@uniud.it
Compilatore del procedimento: Nome Cognome - nome.cognome@uniud.it
via Palladio 8, 33100 Udine (UD), Italia - t +39 0432 556306 - +39 0432 556214 - www-uniud.it
CF80014550307 P.IVA 01071600306 ABI 02008 CAB 12310 CIN R c/c 000040469443

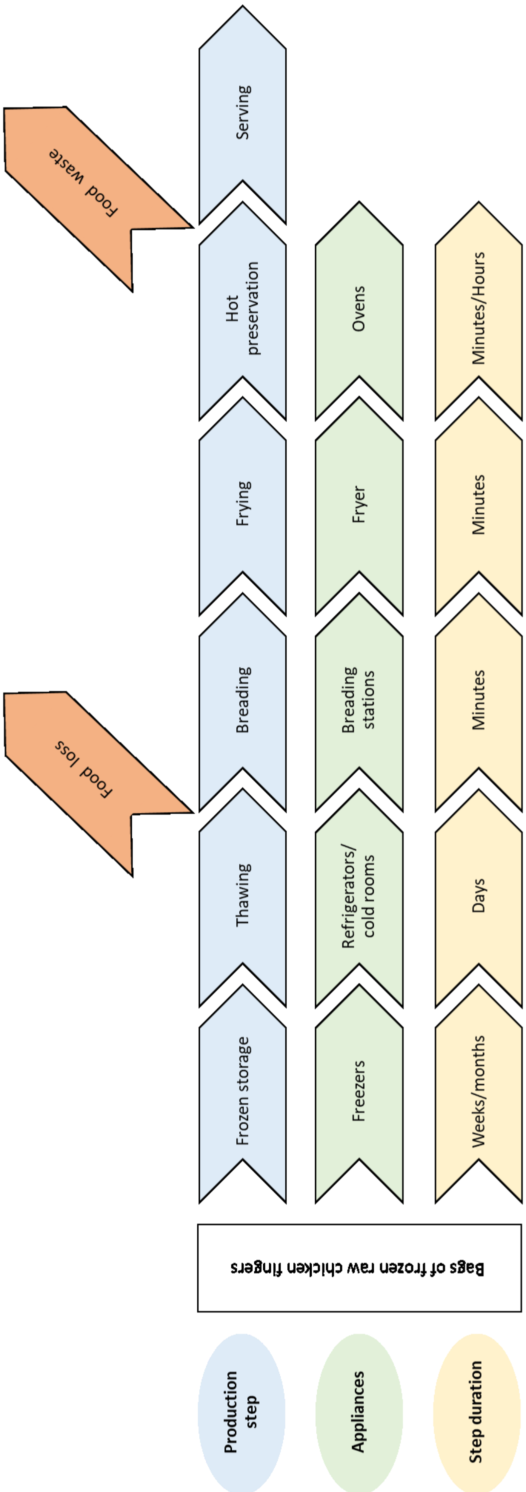


Fig. 2 Quick service restaurant production steps for fried chicken fingers, involved appliances and duration of each step. Main step of food loss and waste are also shown.

Large-size packages (from 2 to 3 kg) of raw frozen chicken fingers are received in the restaurant and stored in freezers. Food service operators, based on the needs, move part of the bags in refrigerators or cold rooms, where they are left for long times (from hours to days) until food is completely thawed. Bags are then opened, and chicken fingers are breaded - optionally using dedicated appliances called "breading stations" - just before frying. This is performed to promote the formation of a crust upon frying while keeping a moist interior (Fiszman & Salvador 2003; Vitrac, Trystram, & Raoult-Wack. 2000; Wang 2005). Fried chicken fingers are either immediately served to customers or kept for short time in hot preservation ovens. This is done to ensure service within few minutes from the order even during peaks in customer number but may lead to remarkable food wastes when the quantities of prepared food do not match the needs. However, since breading and frying steps have a short duration and can be performed almost simultaneously with service, the quantity of food to be fried can be controlled and these food wastes may be partly limited. Conversely, food losses after thawing are more difficult to control. In fact, due to the long duration of the thawing step, food service operators are required to decide well in advance how much frozen food has to be moved from the frozen storage to the thawing chamber. With the aim of managing peaks in consumer number, an exceeding quantity of food is typically thawed. After a relatively short time, thawed food excess must be discarded to avoid perceivable deviations from expected food quality consistency and to avoid food safety issues. Result is that food losses might be particularly high, depending on the operator planning skills. Moreover, the long duration of the thawing step implies that a considerable amount of food must be thawed simultaneously to match the needs of each working day. From the restaurant management point of view, this results in considerable space of the restaurant dedicated to refrigerators or cold rooms (Fig. 1) and consequentially in higher rent/lease expenses. From these considerations emerges the need to improve thawing process to better match thawing time and space needs of food service operators. In particular, QSR operators demand for appliances reducing thawing times, possibly within hours, with reasonable costs for energy consumption, high productivity and no evident depletion of food quality.

1.3 Freezing-thawing of meat: motivations and effects

A non-negligible part of meat and poultry products is wasted every year, also at the food service level, due to spoilage, with a significant economic and environmental impact. Main mechanisms of spoilage for fresh meat are microbial spoilage, lipid oxidation and autolytic enzymatic spoilage (Dave & Ghaly 2011). To minimize these mechanisms, preservation techniques are used. These are based on control of temperature, water activity or use of chemicals/biopreservatives. Freezing is a common practice for improving the management of food products intended for food service and retail. In general, frozen food may be cooked as it is, e.g. par-fried French fries, or thawed, especially for animal products as chicken or fish. Shrestha, Schaffner and Nummer (2009) reported that thawing is required before high temperature cooking processes, as frying or grilling, to ensure that meat products are properly cooked in the inner part without overcooking the outer one. Furthermore, thawing is needed when other preparation steps are necessary before cooking. Examples are trimming of food or applying coatings as breading or batters. After freezing-thawing processes, the quality attributes of foods should be retained as close as possible to those typical of fresh, non-frozen products (Eastridge & Bowker 2011; Li et al. 2014). However, freezing, frozen storage and thawing are known to alter food structure and quality.

Even though freezing is one of the least aggressive preservation methods, it results in a modification of food quality properties, mostly due to ice crystals formation (Oliveira, Gubert, Roman, Kempka & Prestes, 2015). The latter begins in extracellular fluids of fresh tissues, because they are less concentrated than intracellular ones and thus have lower freezing point depression. As freezing proceeds, extracellular solute concentration gradually increases, triggering water migration from the intracellular region to the extracellular one, resulting in cells dehydration. Moreover, extracellular ice crystals increase in volume deforming cell shapes and increasing intercellular areas, impairing tissue integrity by mechanical damage. The magnitude of the latter depends on food nature and freezing rate (Fig. 3), with slow freezing leading to more severe damage (Fuchigami & Teramoto 1997; Reid, 1996; Wu, Zhang, Adhikari, & Sun, 2017). In addition, low freezing rates enhance weight loss by sublimation of superficial ice in non-adhering packaged products. This is a consequence of a different temperature of food and cooling air, leading to a difference in surface water vapor pressure. Ice sublimation forms a porous dehydrated layer on food surface which alters food physical and sensory characteristics (Campañone, Salvadori & Mascheroni, 2001).

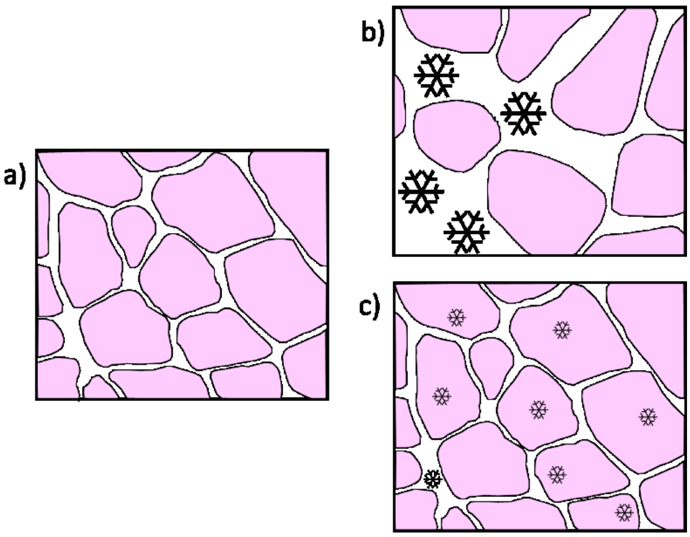


Fig. 3 Schematic illustration of fresh animal (a) tissue and the structural effect of slow (b) and fast (c) freezing.

Typically, frozen products are stored for weeks or months before use. Part of this time occurs in restaurant freezers, which are opened many times every day.

Consequently, products may be exposed to temperature fluctuations, which lead to ice recrystallization cycles. The distribution of ice crystals within products changes over time, with eventual formation of uneven big extracellular crystals, affecting frozen food quality (Alvarez and Canet 1998; Gormley, Walshe, Hussey, & Butler, 2002; Van Buggenhout et al. 2006a, 2006b; Ullah, Takhar, & Sablani, 2014). In addition, air and food surface temperatures fluctuation inside the freezer lead to further ice sublimation and weight loss (Campañone, Salvadori & Mascheroni, 2001). It should also be considered that, in frozen foods, bio-physicochemical processes are not completely inhibited. It is reported that at -20 °C almost 98% of meat water freezes, but more than 10% of muscle-bound water will not freeze. Furthermore, only about 60% of the viable microbial population dies but the remaining population gradually increases through frozen storage (Dave & Ghaly, 2011).

During thawing, frozen water melts, is released, and has to restore equilibrium with the muscle proteins and salts. Furthermore, due to the inflow of water, muscle fibres recover their volume (Ishiguro & Horimizu, 2008). However, depending on freezing and thawing conditions, the thawed product may differ noticeably from fresh tissue. In particular, if muscle proteins are denatured during these steps, water may be not completely reabsorbed. Mechanical disruption of the structure of myosin was identified as the main factor leading to water loss (Honikel, 1998; Lee, Saha, Xiong, Owens, & Meullenet, 2008; Ali et al. 2015). In addition, decrease in the extractability of the proteins, aggregation of myofibrillar proteins, formation of disulphide bond and cross-linking may occur. It was also observed that, if the formation and growth of ice crystals ruptured muscle fibres membrane upon thawing, these entail the formation of wide channels for non-reabsorbed water; while if the rupturing involved cell walls, a release of intracellular components takes place (James & James 2010; Ali et al. 2015). Thawing conditions, especially high or mild temperatures, can result in additional denaturation of proteins or bacterial activity that further threaten tissue integrity. Moreover, thawing rate was reported to affect thawing loss, but different implied mechanisms were presented (Ngapo, Babare, Reynolds, & Mawson, 1999; Alizadeh, Chapleau, De Lamballeire, & LeBail, 2007; Farag, Duggan, Morgan, Cronin, & Lyng 2009; Leygonie, Britz, & Hoffman, 2012). It was hypothesized that low thawing rates may result in structural damage through ice recrystallization and protein denaturation, leading to reduced Water Holding Capacity (WHC) and higher exudate. By contrast, it was also suggested that rapid thawing may hinder extracellular water reabsorption, which is a slow process, leading to higher exudate especially for small meat samples (Gonzalez-Sanguinetti, Añon, & Calvelo, 1985; Ambrosiadis, Theodorakakos, Georgakis, & Lekas, 1994; Farag et al. 2009). One of the most important quality indicators for thawed meat is thus drip loss, which is assumed to give a measure of meat structural damages during freezing and thawing. Moreover, drip loss is directly proportional to the muscle WHC. Poor WHC leads to meats with lower product yield and consumer acceptability (e.g. perceived tenderness, colour and texture) and higher losses of vitamins and minerals (Ferreira, Canet, Alvarez, Tortosa, 2006; Lagerstedt, Enfält, Johansson, & Lundström, 2008; Lee et al. 2008; James & James, 2010; Leygonie et al. 2012; Bedane, Altin, Erol, Marra, & Erdogdu, 2018; Jia, Wang, Yoon, Zhang, & Li, 2018).

Another fundamental parameter for the acceptance of meat is tenderness (Cavitt, Muellenet, Xiong, & Owens, 2005; Pathare & Roskilly, 2016). The latter is, in general, influenced by several factors: (i) length of the sarcomeres; (ii) integrity of myofibrils, which affects actomyosin toughness; and (iii) integrity of the connective tissue, which contributes to the background toughness (Zhao et al., 2012). During freezing and frozen storage, water movement into extracellular spaces results in shrinkage of muscle fibres. Moreover, damage of muscle cells causes the release upon thawing of enzymes from mitochondria into the sarcoplasm. Particularly, the release of proteases (calpains and cathepsins) hydrolyses myofibrillar proteins and leads to quick textural changes. In addition, the above-mentioned protein modifications also lead to decreased swelling, increased toughening and reduced resistance to deterioration of meat during subsequent processing compared to non-frozen meat (Alizadeh et al 2007; Sriket, Benjakul, Visessanguan, & Kijroongrojana, 2007; Li et al. 2014). Nonetheless, contradictory data are reported on the effect of freezing-thawing on meat tenderness (Eastridge & Bowker, 2011). Explanation given is that meat tenderness is affected by many factors, as pre-freezing meat aging, freezing rate, duration of frozen storage and recrystallization phenomena (Leygonie et al., 2012; Gambuteanu, Borda, & Alexe, 2013; Augustyńska-Prejsnar et al., 2018a). In addition, freezing and frozen storage conditions, as packaging, temperature and enlightening, may also affect meat colour and stability, so that thawing does not allow recovering of original product appearance (James & James 2010). It is noteworthy that colour is important for the market value of some thawed food items, as salmon fillets and meat, at their point of sale (James & James 2010). However, it has a limited importance for products destined to cooking.

1.4 Effect of thawing on the quality of fried meat

Deep frying is a cooking technique in which food floats in fat at temperatures of 150 - 190 °C until its core reaches the desired temperature. Fat is a dense medium, with a relatively high heat capacity and able to store large amounts of energy (Vitrac, Trystram, & Raoult-Wack, 2000). The resulting high heat flux density, in combination with food's water loss, thermo-oxidation reactions, change of colour and modification of lipid profile, is accountable for the typical sensory characteristics of fried food (Kassama & Ngadi, 2005; Pedreschi & Moyano, 2005b; Chiou, Kalogeropoulos, Boskou, & Salta, 2012; Fan & Eskin 2012; Pawar, Boomathi, Hathwar, Rai, & Modi, 2013). Crisp crust, soft core and golden colour of deep-fried food are highly appreciated by consumers, while its high fat content is unpopular due to public awareness of excessive fat consumption relation with health disorders (Mellema 2003; Lloyd, Farkas, & Keener, 2004; Wang, 2005; Miranda et al. 2010). Moreover, high fat uptake may negatively affect textural properties of fried food and is also undesirable for food service operators (Kita, 2014). In fact, fat represents an expensive resource and additionally manual work or energy are needed for fryers refilling operations.

Quality of fried food is controlled by many factors, either connected with the nature of the ingredients or with technological operations affecting food structure (Dana & Saguy 2006; Ziaiifar, Achir, Courtois, Trezzani, & Trystram, 2008; Kita 2014; Oladejo et al. 2017a, 2017b). Porosity and pore size distribution of food, in particular, affect its mechanical, textural and sensory properties as well as thermal conductivity and diffusivity, and mass diffusion coefficients (Kassama & Ngadi, 2004, 2005; Ježek et al., 2009; Alam & Takhar, 2016; van Koerten, Schutyser, Somsen, & Boom, 2015). During frying, pores are developed by evaporation of water and their size increases with time. In part, because a more vigorous evaporation of water is able to disrupt food structure, but also because pores may merge (van Koerten et al., 2015). Fat uptake takes place in these pores either during frying, for capillary mechanisms, or after frying, when pressure inside the pores drops for vapor condensation (Mellema 2003; Vauvre, Kesteloot, Patsioura, & Vitrac, 2014; Dana and Saguy 2006; Debnath, Rastogi, Gopala Krishna, & Lokesh, 2009). In general, the more moisture is removed from the surface, the more fat is absorbed (Ziaiifar et al., 2008). Prolonged frying, however, may lead to shrinkage and collapse of the pores due to denaturation, gelation and agglomeration of proteins. These phenomena may be limited if fat was able to fill the pores in the previous stages of frying, forming a composite structure in interaction with muscle fibres. The evolution of the frying process is hence affected by initial porosity and moisture of food, and pre-frying operations affecting them play a key role in controlling fried food quality. Pre-frying drying and blanching effects on food quality were largely studied, especially to reduce fat uptake (Krokida, Oreopoulou, & Maroulis, 2000; Pedreschi & Moyano, 2005a, 2005b; Schuten, van Gijssel, & Slotboom, 2004; Poushamsian, Ghomi, & Nikoo, 2012). In contrast, the effect of freezing, frozen storage and thawing combination is still scarcely considered in relation to the frying performance, especially for animal products. This is quite surprising considering the aforementioned effects of freezing and thawing on meat. It is, in fact, conceivable that different methods of freezing-thawing food, leading to different degrees of food structure damage and drip loss, may result in different food performance upon frying.

The limited available literature confirms that freezing and thawing affect food performance upon frying. In particular, effect of freezing - without thawing - on frying performances was studied on vegetables and on dough. O'Connor, Fisk, Smith and Melton (2001) and Adedeji and Ngadi (2018) respectively concluded that freezing of French fries affects the depth of fat penetration, and that low freezing temperatures (-82 °C Vs -18 °C) reduce fat uptake, unless freeze-cracking damages product surface. Contrarily, Molina & Bouchon (2016) stated that faster freezing, creating smaller ice crystals, leads to a more porous microstructure of dough, enhancing its fat uptake during frying; they added however that a longer frozen storage would enlarge ice crystals, nullifying the difference. Albertos et al. (2016) observed that freezing of carrots before vacuum frying decreases their moisture, creates a more homogeneous porous structure and increases fat uptake during the pressurization phase due to capillary forces, leading to an improvement of sensory properties and antioxidant capacity.

The effect of freezing-thawing on frying performance was examined by Maity, Raju and Bawa (2012) on vegetable snacks (coated before freezing), in comparison with unfrozen samples. They observed a reduced WHC of the product and higher water migration in the coating, which led to hard-textured crust and deformed/ loosened texture of fried snacks. Abdul Hamid, Omar and Sanny (2019) studied the effect of different thawing methods (microwave, room temperature and chiller) on French fries. Although they did not observe significant differences, microwave thawing showed the best results, with lower acrylamide formation and fat uptake. They suggested that the result is possibly related to the shorter time needed to fry microwave-thawed fries, which prevented the diffusion of moisture from the center to the outer layers during frying. García-Arias, Alvarez-Pontes, García-Fernández and Sánchez-Muniz (2003) observed that different thawing methods (refrigerator or microwave) of sardines affected their lipid-protein bonds in a dissimilar way upon frying, with an effect on the exchange between food fat and frying fat, ultimately influencing proximate composition of fried food. Moreover, they observed a significant influence of thawing method on amino acid losses caused by frying and they suggested a possible influence on protein digestibility due to an increase of disulphide bonds and other stable covalent links. More recently, Lee, Han, Jung, Lee and Chung (2020) studied the effect of different thawing methods (microwave, refrigerator or water immersion) on the acrylamide and PAHs formation in different non-breaded chicken parts (breast, thighs or wings) fried by air frying or deep frying. They concluded that, although some differences were observed in chicken thighs, the thawing method did not affect the formation of the abovementioned process contaminants.

1.5 Thawing methods

Several thawing methods were proposed and tested for domestic, industrial and laboratory applications. The ideal thawing method for QSR should guarantee primarily short thawing times (Fig. 4). Additionally, food yield, microbiological safety and appearance should be considered, even though the latter may be relatively less critical since thawed food is intended for further processing. Other fundamental criteria comprise processing implications, as effluent disposal, capital and operating costs - comprising space availability - and lastly versatility, intended as ability to process different types of food.

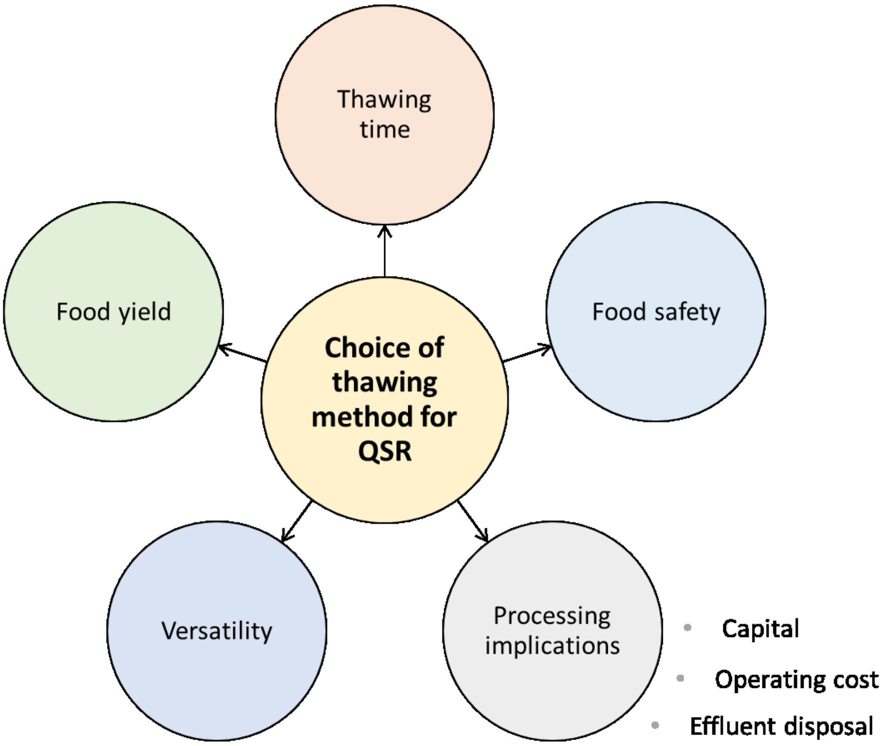


Fig. 4 Criteria for the choice of a thawing method for quick service restaurants.

Target of thawing is to bring the whole product temperature just above its freezing point, usually up to a conventional end point of 0 °C. To this aim, heat must be added to food, in a quantity sufficient to just pass the phase transition of water from solid to liquid. Depending on the heat transfer method, thawing methods can be classified into two major categories (Fig. 5): traditional or volumetric methods. Traditional thawing processes add heat to food through its boundary layers, while the second group distributes and generates heat all over the inner domain of the food (James & James 2010; Backi 2017).

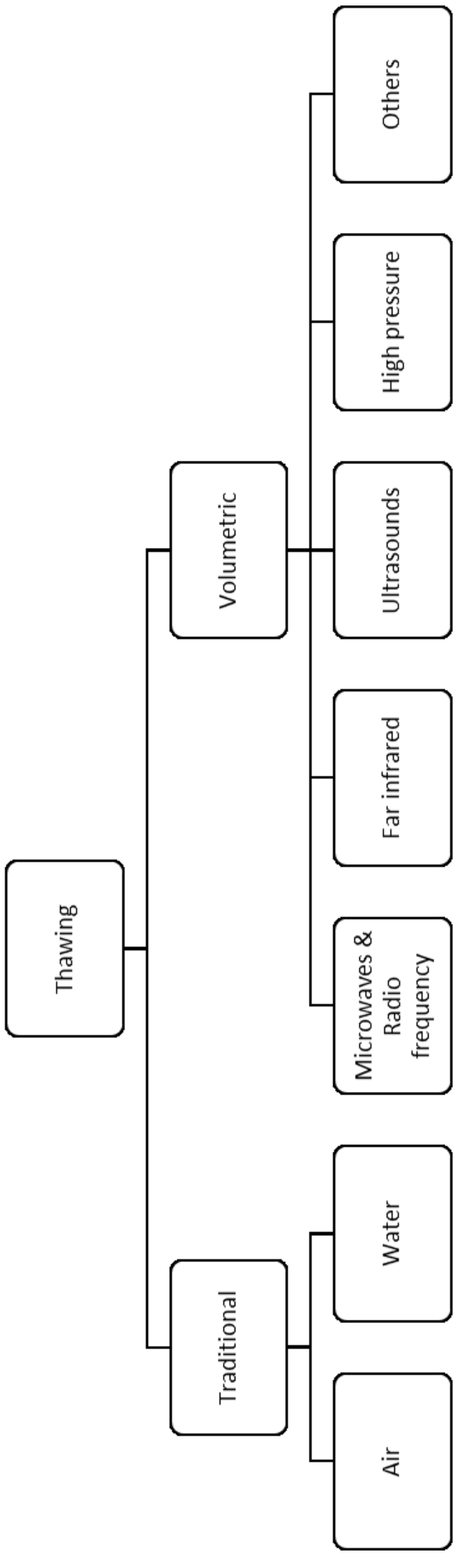


Fig. 5 Thawing methods.

1.5.1 Traditional thawing methods

In a traditional thawing process, as refrigerator thawing used in food service, the product surface gains heat from the surrounding medium by convection (and eventually irradiation) and then heat is conveyed into the product mainly by conduction. Due to the most common values of thermal properties (density, thermal conductivity, specific heat) of food, the last phase can become the “bottle neck” of the overall heat transfer (Krokida, Panagiotou, Maroulis, & Saravacos, 2001; ASHRAE, 2006). A phase-change interface between frozen and thawed food areas will be first formed on the food surface when its temperature reaches the melting point. The interface will then move inwards as the food continues to gain heat. Eventually, the interface vanishes at the centre as the thawing process finishes. The analysis of the thermal behaviours is classified as a moving phase-change interface heat transfer problem. Actually, in food, phase-change does not occur at a single melting point, but over a temperature range, due to the decreasing concentration of undissolved solids, increasing the melting temperature (Leung, Ching, Leung, & Lam, 2007). Generally, thawing is slower than freezing. Motivation is that frozen water is a better heat conductor than liquid water, thus, after the thawing process has started, the outer layers of the product act like a resistance to the heat flow (James & James 2010). Thawing rate is controlled by two main parameters outside the product: (i) the surface heat transfer coefficient and (ii) the temperature difference between the food and the surrounding medium (Ersoy, Aksan, & Özeren, 2008). The latter should be chosen considering some general rules: melting point of the product gives the lower bound while, to define the upper bound, it is important to prevent the development of microbial flora and to reduce the impact of enzymatic activity which increase at milder temperatures. Different thawing temperatures were described in literature. Ersoy, Aksan and Özeren (2008) and Alizadeh et al. (2007) reported that a medium temperature below 15 °C helps to prevent the development of a microbial flora. However, the little temperature difference between frozen sample and environment leads to slow thawing processes. To reduce thawing times, it is therefore necessary to increase the surface heat transfer coefficients. One option is to select a more efficient thawing medium. Considering the same fluid-dynamical conditions, water has a higher heat transfer coefficient than air (approximately up to two orders of magnitude more), and consequently water thawing allows a noticeable reduction of thawing time (e.g. from 22 to 2 hours) (Anderson, Sun, Erdogdu & Singh, 2004a; Leung et al., 2007; Oliveira et al., 2015). This thawing method is widely used industrially for fish thawing. However, a connection to the water supply and drain systems is required, possibly implying costs for the modification of the food service outlet layout. Moreover, water thawing is generally scarcely controllable, with potential cross contamination of microorganisms (Shreshta et al., 2009; Backi, 2017), and implies excessive discharge of water (Leung *et al*., 2007). As reported by Martinelli, Cavalli, Pires, Proença, and Proença (2012) and Lo, Chan and Wong (2011), water thawing accounts for a consumption of 76.2 litres of drinking water for each kilogram of thawed meat and 30% water consumption in a restaurant. Alternatively, vacuum and contact thawing may be applied. Vacuum thawing is based on the heat provided by water condensation on food surface. Pressure in the thawing chamber is adjusted to control water boiling temperature, allowing thawing at desired temperature. However, risk of heat-damage is reported if pressure and steam are not carefully controlled (Backi, 2017). Contact thawing instead, requires inserting blocks of frozen food between heated metal plates. Food is not directly in contact with the thawing media, but must be in direct contact with both plates, thus the product shape may limit the efficiency of the heat transfer. Furthermore, unpacking of products and loading of the plates are considered time consuming operations (Backi, 2017). Another option to increase the surface heat transfer coefficients during thawing comes from a more efficient application of air as a thawing medium.

Indeed, air thawing is preferable as it is more easily controllable and implementable in food service outlets, without costs for effluents management or modification of the outlet layout. Moreover, costs and energy consumption are expected to be lower as compared to any alternative medium. For the reduction of thawing time, it is therefore necessary to increase air speed and its impact angle on the product surface, as occurs upon air blast thawing (6-10 m/s) and, at a higher extent, upon air impingement thawing (at least 10-50 m/s). Air blast is in fact reported to be widely used for industrial fish thawing and it was reported to give good results in terms of colour and drip loss for salmon (Alizadeh et al. 2007; Backi, 2017). It could be expected that air impingement thawing has a high potential in further decreasing thawing time, however this method is still subject to research, and experimental data is at date hardly available (James & James, 2010; Backi 2017).

1.5.2 Volumetric thawing methods

In a volumetric thawing process, different technologies may be applied, generally leading to a reduction of thawing times. A well-known example is given by microwave thawing (900 -3000 MHz), which is occasionally used for home and food service thawing (James & James, 2010). Microwave heating is generated through friction by dipole rotation and by migration of ionic species to region of opposite charge. Its application for thawing is limited by a depletion of food quality and yields caused by run-away heating, which takes place over the initial thawing point temperature due to preferential absorption of microwaves by liquid water (Xia, Kong, Liu, Diao, & Liu, 2012; Boonssumrej et al., 2007; Srinivasan, Xiong, & Blanchard, 1997). Similarly, radio frequency heating (1-300 MHz) has received mixed reports in terms of its effect on drip loss (Farag et al. 2009). It showed favourable performances for tempering food to final temperatures from -5 to -2 °C but has limited application for thawing due to runaway heating, more severe in high fat foods (Wu et al., 2017; Bedane et al. 2018). A careful optimization of the electrodes configuration and moving conveyor belts, or other means of food movement, may limit the run-away side effect (Wu et al, 2017; Bedane et al. 2018). These solutions, however, are more easily implementable industrially than for food service. Ohmic heating, also known as electro-heating or Joule heating, employs electric current passing through foods with high electrical resistance. For fish thawing, it was reported that Ohmic thawing is applied only for the final stage of thawing (e.g. from to -3 °C), as frozen fish is a poor conductor of electricity. This technology is energy efficient and has no limitations of penetration depth, however the product has to be shaped as a block, to be put between the plates and avoid local overheating (James & Lames, 2010; Backi, 2017). Moreover, the electrostatic field may cause electrolysis of the expensive electrodes. The novel method is promising and improves food WHC but is still in an early stage of research (Jia, Liu, Nirasawa, & Liu, 2017; Li & Sun, 2002). High voltage electrostatic field generates corona wind, which produces vortices and turbulence, enhancing heat transfer. The process is energy efficient and can also inhibit microbial growth (Hsieh, Lai, Ho, Huang, & Ko, 2010; He, Liu, Tatsumi, Nirasawa, & Liu, 2014). However, this method is also still at an early stage and more research is needed (Backi, 2017; Wu et al., 2017). Moreover, a release of ozone was observed, which may oxidize food surface affecting food flavour and colour (Mousakhani-Ganjeh, Hamdami, & Soltanizadeh, 2016; Jia et al. 2017). High pressure was also applied, in chambers filled with a pressure transmitting fluid, for thawing at low temperatures (Backi, 2017; Wu et al., 2017). However, reduction of post-thawing WHC, protein conformational changes and denaturation as well as colour and texture deterioration were reported (Fernández-Martín, Otero, Solas, & Sanz, 2000; Leygonie et al., 2012). Moreover, this is still an expensive technology (Jia et al. 2017). Ultrasound assisted water thawing reduces thawing times as compared to water immersion thawing. In addition, with a correct tuning of frequencies and power, meat technological and textural properties can be preserved also after cooking (Gambuteanu & Alexe, 2015). However poor penetration, localized heating and high-power requirements were reported (Li & Sun, 2002). Lastly, the system requires a water bath which may be space consuming and of difficult management for QSR.

1.5.3 Considerations of industrial applicability of different thawing techniques

In general, at the moment, most volumetric thawing methods are still not suitable for large-scale applications (Backi, 2017) and are even less available or applicable for food service. In particular, they do not match food service needs due to high operating costs - both directly or indirectly for the space requirements - as well as to possible development of side effects such as uneven thawing, discolouration or oxidation. It is possible that, with evolution of technologies, a reduction of dimensions and costs will be possible, and they will become convenient. However, at present, it is still preferable to use traditional air thawing for its easier applicability and food quality preservation. In particular, increasing air velocity as in air impingement thawing, appears the most promising alternative to conventional refrigerator thawing.

1.6 Air impingement

Air impingement systems exploit jets of air, at high velocities, impinging perpendicularly on the surface of products (Sarkar, Nitin, Karwe & Singh, 2004). Impingement reduces the thermal boundary layers surrounding the products surface, increasing convective heat-transfer coefficients and allowing faster heat-transfer processes. Systems (Fig. 6) are equipped with: means to generate the airflow and to control the air temperature and speed; a plenum chamber with pressure difference forcing air through the nozzles; a plate with nozzles which can be of different dimension, shape and alignment; grids or conveyor belts where the products are placed to be impinged by upward, downward or both directional jets; (Salvadori & Mascheroni, 2002).

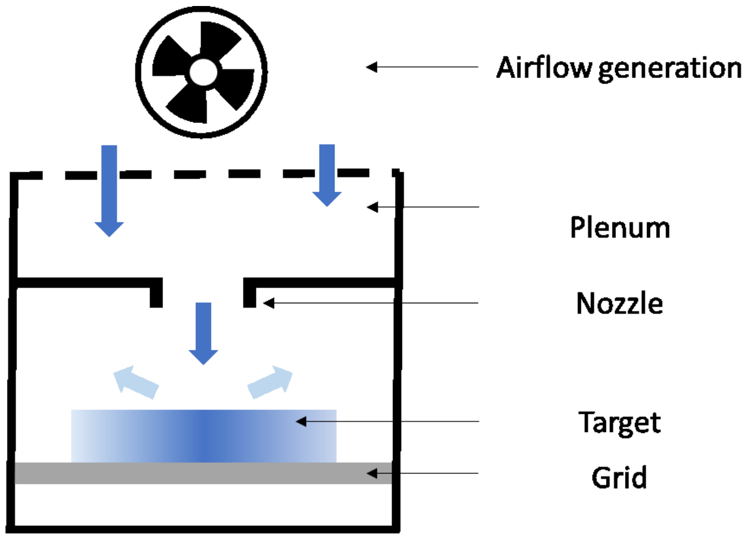


Fig. 6 Schematic representation of an air impingement system with downward jet.

The heat transfer rates can be varied either by adjusting flow rates and temperature differentials or by adjusting several geometric parameters (Millsap & Marks, 2005). Jet flows can be classified according to Reynolds number, as laminar or turbulent, and according to exit conditions of the jets from the chamber, as confined or unconfined.

1.6.1 Food industry applications of air impingement

Air impingement, commonly turbulent ($N_{RE} > 10000$; hereinafter N_{RE} is intended to be calculated at nozzle diameter), is used for food applications as baking, toasting, drying and freezing (Sarkar, Singh 2003; Anderson & Singh 2006a; Marazani, Madyira, & Akinlabi, 2017). In these applications, typical nozzle exit velocities range from 10 to 100 m/s and temperature ranges from -50 °C (freeze) to 400 °C (baking).

Industrial implementations use tunnel machines working in continuous mode, while food service appliances mainly work in batch mode. For food applications shorter nozzles are preferred, as longer ones were reported to be more difficult to clean, promoting the blockage and being less hygienic (Marazani et al. 2017). In air impingement, as well as heat transfer, also the mass transfer is enhanced and varies radially and in depth from the jet. To guarantee an acceptable quality of the products, it is important to ensure that the surface of food does not dry excessively (Anderson & Singh, 2006b; Marazani et al. 2017). To this aim, it was reported that for unpackaged food, confinement of the jets may be advantageous, as it may reduce drip loss by conserving moisture (Sarkar & Singh 2003). Additionally, the composition and/or physical properties of food are important for mass transfer phenomena; examples are foods with a skin/peel or surface fat on meat, which has a much lower thermal conductivity and higher specific heat capacity than the rest of the meat. Also, the dimensions of the products are important, with air impinging being more efficient for thin products, while on thicker products an excess surface dehydration could be observed. Moreover, for thicker products the conduction "bottle neck" effect is enhanced. Ideally the shape of the products should be able to receive multiple jets perpendicularly on its surfaces to improve the heat-transfer efficiency (Salvadori & Mascheroni 2002).

1.6.2 Heat transfer of single and multiple jets

The flow field/pattern of a single impingement jet can be divided in three regions (Fig. 7): (i) the free jet region, (ii) the stagnation region and (iii) the radial flow region (also known as wall-jet-region or lateral-spread-region). In the first part of the free jet region (which is called potential core region), the flow has no vorticity; further on, the free shear with stagnant air leads to a formation of turbulence and entrainment phenomena are promoted (Zuckerman & Lior, 2006). The turbulence level increases along the jet length and its peak shifts (developing flow region) until it reaches the jet centre axis (developed flow region). In the stagnation region, the jet impinges and is deflected. This region starts at a distance of 1 - 1.5 nozzle diameters (D) from the impinging surface, as the deceleration of the impinging jet begins. There is a steep decrease of the axial velocity and thus an increase in the static pressure. Just after stagnation, in the radial flow region, the negative pressure gradient causes rapid increase in the radial velocity; far ahead, because of the wider area available and the viscous drag at the wall, there is a drop in velocity (Sarkar *et al* 2004).

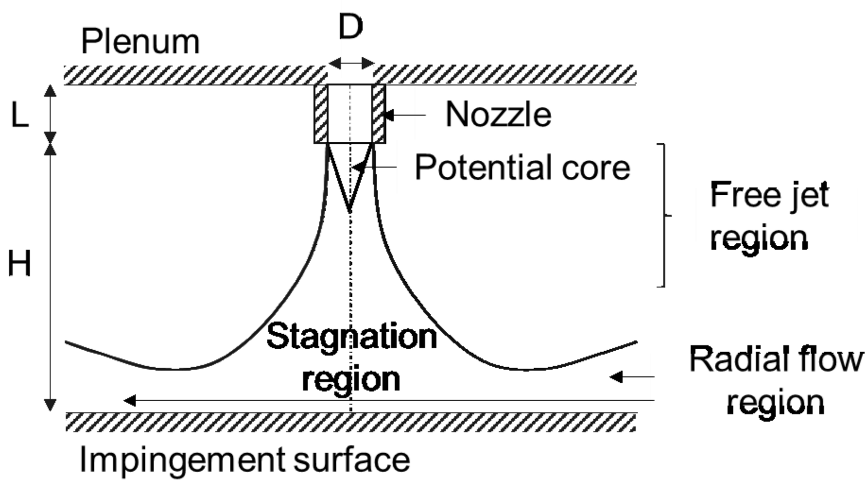


Fig. 7 Schematic diagram of single impingement jet regions.

Heat transfer coefficient for a single jet is maximum in the stagnation region and declines radially (by 30 - 40%) to a minimum in the wall jet region (Marazani et al. 2017). This is caused by the high deceleration in flow in the stagnation region, resulting in a sharp temperature gradient in the thermal boundary layer. The convective heat-transfer coefficient h equation (Eq 1) can explain this phenomenon:

$$\text{(Eq 1)}\ h = \frac{k \left.\frac{\partial T}{\partial y}\right|_{y=0}}{Tair - T\, surface}$$

Where: T is temperature, y is vertical position, k is thermal conductivity of the air. In the stagnation region, the numerator is large because of the sharp temperature gradient at the fluid-surface interface, due to the reduction of the boundary layer. In the radial flow region, the flow develops: the boundary layer grows thicker, resulting in milder gradients and a decline in the heat-transfer coefficient. The maximum and this radial decline are a function of Reynolds, H/D ratio (H = nozzle to food distance; D = nozzle diameter; see Fig. 7), nozzle type and temperature conditions. Typically, in impingement systems, multiple jets are used. The difference in the flow field compared to a single jet is caused by the interactions between the surrounding jets. These interactions are classified depending on their position: 1) mixing domain before impingement, 2) laterally, after impingement (in some cases leading to "upward jet fountains"; see Fig. 8), 3) interactions due to asymmetry or absence of exhaust outlets between the jets. In these cases, the spent air flowing toward the exhaust interacts with the impingement jets on its path (cross flow) (Sarkar et al. 2004). The interactions are generally a drain of the energy of the jet. A proper design of the nozzle arrays and of the exhaust can reduce the interactions and limit the negative effects of cross flow. For example, cross flow effects are enhanced by circular nozzles and by the accumulation of spent air inside the flow field.

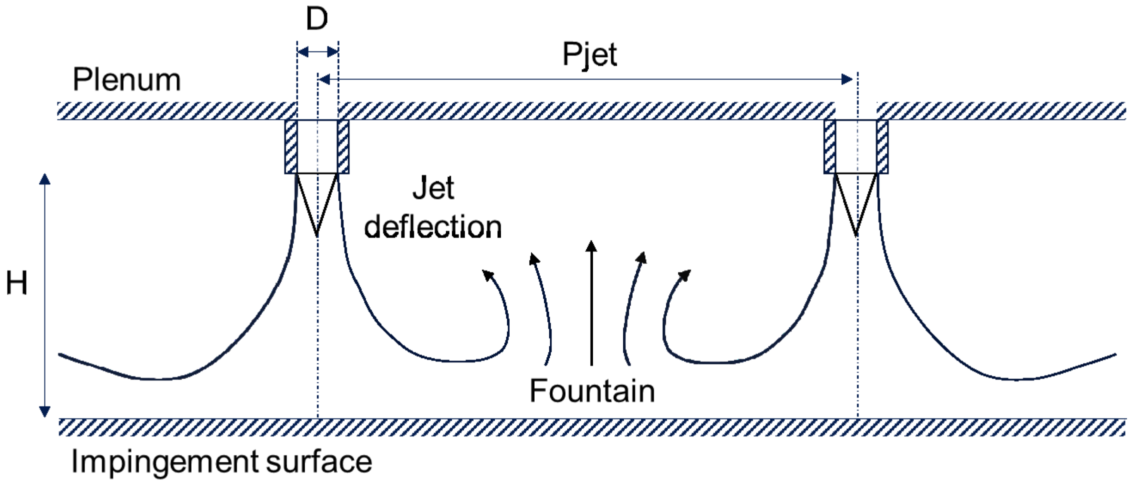


Fig. 8 Example of multiple jet impingement jet interactions.

In multiple jets systems, the maximum heat-transfer coefficient may be not in the stagnation region, due to the higher heat transfer of turbulent flows caused by interaction between jets. Many factors, as nozzle jet geometries, affect the heat transfer. For example, for slot jets, Pjet/H ratio (Pjet = pitch between nozzles) was found to be optimal from 1 to 1.5; likewise, high and uniform heat-transfers were reported for H/D ratio of 6 to 8, while smaller ratios cause confinement and bigger ones cause excessive energy dissipation (Sarkar et al 2004). Optimization of all the parameters through experimentation is rather difficult and computational fluid dynamics (CFD) are used to simulate flow fields and heat transfer. Most of the studies of the flow field are based on flat target plate geometry, while only few approaches have been developed to study the typical food-processing systems. The latter, being characterized by the interaction of impinging jets with different surface geometries and the presence of multiple objects under different jets in certain temperature ranges. Moreover, few studies focused on mass transfer during impingement processes, and food dehydration is often derived from empirical correlation between heat and mass transfer coefficients (Sarkar et al 2004). When considering phase transition processes, additional issues for modelling rise, requiring a more complex solution routine for heat transfer inside the product and more challenging boundary conditions at the food-fluid flow interface.

1.7 Air impingement thawing

Air impingement (AI) application as a thawing method was only studied since the early 2000s. Heat transfer coefficients related to AI in freeze-thaw regimes were at first measured by Sarkar and Singh (2003), using copper and steel plates. Subsequently, Anderson, Sarkar and Singh (2004b) used computational fluid dynamics (CFD) to simulate fluid flow and heat transfer during AI thawing. In another work, Anderson & Singh (2006a) studied effective AI heat transfer coefficients using an inverse heat transfer method on a Nylon disk. In addition, they used disks of Tylose gel, a meat analogue product (Riedel, 1960), to develop a two-dimensional model for AI thawing (Anderson & Singh, 2006b). Heat-transfer coefficient values of AI thawing were demonstrated to be much higher (30-180 W/m^2K) than those associated to thawing in a refrigerator (about 10 W/m^2K) (Anderson et al., 2004a, 2004b; Anderson & Singh, 2006a). More recently, a mathematical model of AI thawing of Tylose bricks, combining CFD and Finite-Difference heat-conduction, was developed by Tiberi (2018). The model was validated in an air impingement prototype designed for food service application. Especially, air temperature, speed and distance of food to nozzles effects were modelled in relation to the sample temperature uniformity, the risk of overheating parts of the sample and total thawing time.

Available data regarding AI thawing effect on real food is still very scarce. Góral and Kluza (2003), Góral and Domin (2005) and Góral (2008) evaluated, on a laboratory scale, the application of air impingement at 15 °C for thawing fruits and vegetables. They concluded that thawing times resulted shorter or comparable to those associated to water thawing at the same temperature. A reduction of food thawing loss and good sensory properties were also reported. To our knowledge, no data is currently available about the impact of air impingement thawing on the quality of meat products.

1.8 Conclusions

Conventional refrigerator thawing performed in quick service restaurants (QSR) is characterised by long duration and represents a source of food loss as well as a cost, direct and indirect through its space requirements. Improvement of thawing process should consider, along with thawing time, food processing implications and should avoid impairment of food performances both after thawing and after further cooking. In fact, freezing and thawing, depending on the methods and conditions used, might alter food structure and hence may affect their performances also after cooking. Amidst traditional and volumetric thawing methods, air thawing is still the most promising one for QSR. Its performances can be improved increasing air speed, as occurs in air impingement thawing. Although this technique has the potential of reducing thawing time, information on its impact on food is currently lacking. Especially, no information is available on its effect on meat products just after thawing and upon successively cooking.

Chapter 2 Aims and structure of this project

Aim of this work was to evaluate air impingement thawing as an alternative to conventional refrigerator method for quick service restaurants. In particular, the target was to verify if this thawing method allows a reduction of thawing time without impairing food performances after thawing and after subsequent frying. Experimental activities were organised according to Table 1. In the first phase, an air impingement thawing prototype was developed considering requirements for food service application. In the second experimental phase, a novel optimization approach was used to define the combinations of air impingement thawing process parameters (thawing cycles) to be used for thawing chicken fingers. The latter were selected as case of study, for their wide diffusion and popularity. In particular, bags of frozen chicken fingers surrounded by bricks of a meat simulant, were used as a representative load for food service. Validation of the selected thawing cycles was performed by comparison of predicted and experimental thawing time and temperature of chicken fingers in phase three. In this phase, the comparison of air impingement, refrigerator and microwave thawing time was also performed. Microwave thawing was chosen as a second reference, considering its occasional use in food service and well-known high thawing rate. In the fourth experimental phase, performances related to food structural modification upon thawing by air impingement were compared to those of the refrigerator or microwave thawed controls. Successively, in the fifth part, chicken fingers thawed by air impingement, refrigerator or microwaves were fried and their main quality attributes were compared. In the last experimental part, to further validate the observed results and to assess the versatility of air impingement thawing method, other popular commercial food service foods (French fries, squid and cod filet) were considered. The performance after thawing and frying of these products thawed by air impingement was compared to that of the foods thawed by thawing methods occasionally employed in food service (refrigerator, microwaves, running water and room temperature).

Table 1 Experimental activities of this Ph.D. project.

Topic	Chapter
Development of an air impingement thawing prototype for food service. An air impingement prototype for food service was developed. Explanation of design choices and prototype characteristics were given.	3.1
Definition of optimized air impingement thawing cycles. A novel optimization technique was used to identify the most promising combinations of thawing process parameters (thawing cycles), based on chosen performance objectives. Optimization technique set up and resulting optimized thawing cycles were described.	3.2
Validation of optimized air impingement thawing cycles. Experimental and predicted performances of the optimized air impingement thawing cycles were compared.	3.3
Performances of air impingement thawed chicken fingers. Frozen chicken fingers thawed by air impingement, refrigerator or microwave thawing were compared. Performances in terms of thawing loss, WHC, firmness, microstructure and FTIR spectra were assessed.	3.4
Performances upon frying of air impingement thawed chicken fingers. Chicken fingers, thawed by air impingement, refrigerator or microwaves, were coated with breading and fried. Performances in terms of cooking loss, firmness, colour, moisture loss, fat uptake and sensorial scores were compared.	3.5

Efficacy of air impingement thawing on typical thawed-fried commercial food for food service. Commercial food service frozen products (French fries, squid and cod fillet) were thawed by different methods: refrigerator, room temperature, microwave, running water and air impingement. Performances in terms of thawing time, thawing loss, cooking loss, firmness, colour and fat uptake were compared.	3.6

Chapter 3 Experimental activities

3.1 – Development of an air impingement thawing prototype for food service.

Commercial AI appliances for thawing are not yet available on market. Hence, a prototype had to be developed to study AI thawing performances for food service. In this chapter, main requirements for the prototype were defined. In particular, issues relevant to dimensions, compatibility with standard food service trays and minimization of head losses were analysed. Based on the identified target, the factors considered for the development of the prototype used in this project as well as its final characteristics and components were described.

3.1.1 Requirements for a food service prototype

Food service appliances are characterized by relatively small footprint and high productivity. Secondarily, since operators have a quick turnover, an intuitive user interface and automatic/assisted settings of process parameters are considered advantageous. AI appliances are currently used in food service for cooking, especially in combination with other technologies as microwaves. However, no similar application for thawing was commercialized to date. An AI thawing prototype for food service (Fig. 9) was developed by Tiberi (2018) for the verification of a thermal model. The prototype was developed to closely replicate simulations, hence voluminous air ducts equipped with airflow meters were used to strictly control the flow conditions. Also, the plenum - uniform pressure zone before the nozzles plate, necessary to have the same jet from all nozzles - was very large compared to a relatively small thawing chamber (42 cm × 42 cm × 34 cm).

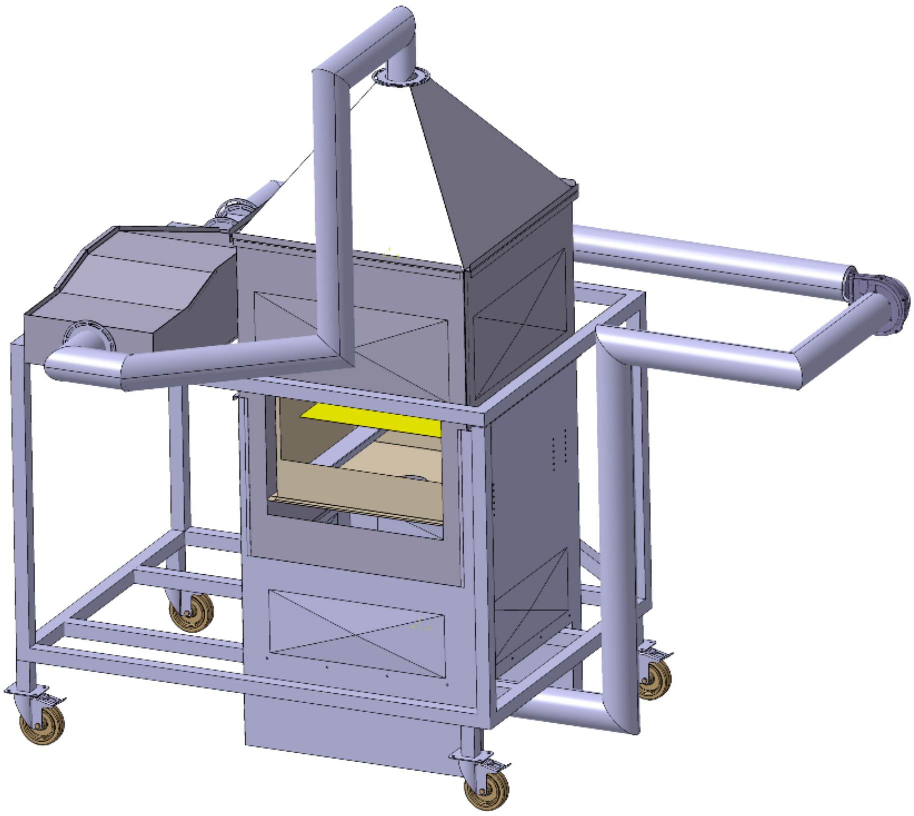


Fig. 9 CAD drawing of the food service air impingement prototype developed by Tiberi (2018) (© courtesy of Emidio Tiberi).

3.1.2 Development of the prototype

Visentin (2018), continued Tiberi's (2018) research, studying the industrial manufacturability of an AI appliance for general application (e.g. baking, freezing) with dimensional limits, while maximizing its thermal exchange and uniformity. Spatial limits of the appliance were initially set to 77 cm × 65 cm × 18 cm for the thawing chamber and plenum, with the requirement to fit one standard gastronorm (GN) 2/1 food service tray (53 cm × 65 cm). Furthermore, production costs were highly taken in consideration. As for the production material, AISI 304 stainless

Responsabile del procedimento: dott. Nome Cognome - nome.cognome@uniud.it
Compilatore del procedimento: Nome Cognome - nome.cognome@uniud.it
via Palladio 8, 33100 Udine (UD), Italia - t +39 0432 556306 - +39 0432 556214 - www-uniud.it
CF80014550307 P.IVA 01071600306 ABI 02008 CAB 12310 CIN R c/c 000040469443

steel, widely diffused for food industry applications, was chosen for its limited thermal dilatation, mechanical properties and resistance to corrosion.

Initially, Visentin (2018) designed a first version of the appliance (Fig. 10). The key element affecting AI heat transfer efficiency is the design of the nozzles plate. In fact, design of the nozzles affects the turbulence and widening of the jet and the length of the potential zone. Minor differences in the manufacture of the nozzles lead to remarkable differences in performances; therefore, manufacturability represented the crucial point for the selection of the configuration. The chosen design was circular, a shape easily made with a punching machine. For food service application, multiple jet configuration was an obligated choice due to the relatively wide target area. However, this configuration led to the necessity to manage the "cross flow" effect (see section 1.6.2). This was solved by means of lateral exhaust outlets on thawing chamber walls. Nevertheless, the design of these outlets had to guarantee their performance also in the most critical conditions of loading, represented by the smallest distances of target to nozzles available. The outlets were therefore maximized compatibly with technological aspects. Finally, a staggered configuration of nozzles was chosen. Second essential component to be designed for the AI prototype was the plenum, which had to be of very limited dimensions. Moreover, this hermetic component inevitably introduces head losses that had to be minimized. Given all these considerations, the prototype design had to guarantee a compromise between heat transfer and head losses.

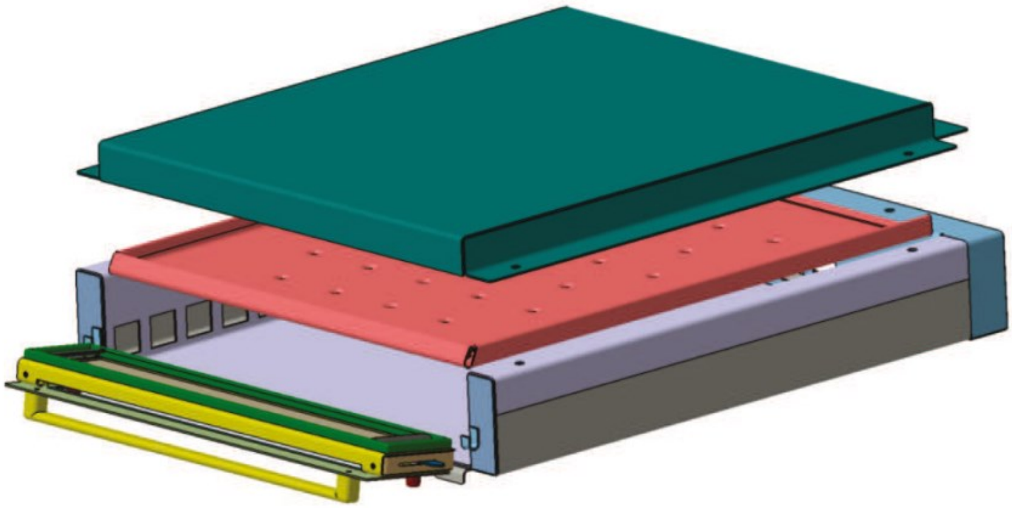


Fig. 10 CAD design of the first version of Visentin air impingment prototype (© courtesy of Alberto Visentin).

Visentin (2018) virtually investigated combinations of prototype parameters, employing Tiberi thermal model (2018) and statistical analysis by DOE (Design of Experiments). Chosen prototype parameters were Reynolds (that expresses the air speed), H/D (D = nozzle diameter; H = distance nozzle to target) and Pjet/D (Pjet = pitch between nozzles). Three levels were chosen for each parameter. As for Reynold 15,000, 20,000 and 25,000 were chosen, for a broad investigation of the overall feasibility limits. For H/D the lowest limit is 2, to have the formation of upward fountains and no interference with exhaust flux. Upper limit was set at 6, due to geometric restrictions. Pjet/D had to be set to limit the “shear layer” interaction between adjacent jets. Moreover Pjet/D determines the number of holes in the nozzles plate and thus affect head losses. Zuckerman and Lior (2006) recommended a ratio bigger than 8 however, due to the geometric constraints, this would have led to a low number of holes, negatively affecting thermal uniformity on the target surface. Thus, a range of 6 - 8 was chosen.

Reynolds resulted to be the most influential parameter for thermal heat transfer and head losses. While, no clear effect on head losses was observed for the nozzle pitch, which showed also a modest effect on average Nusselt (ratio of convective to conductive heat transfer at a boundary in a fluid). Thermal evenness was comparable for observed combinations of parameters. Design of the final version of Visentin prototype (Fig. 11) was consequently based on Reynold and H/D, while Pjet/D was set at 6.

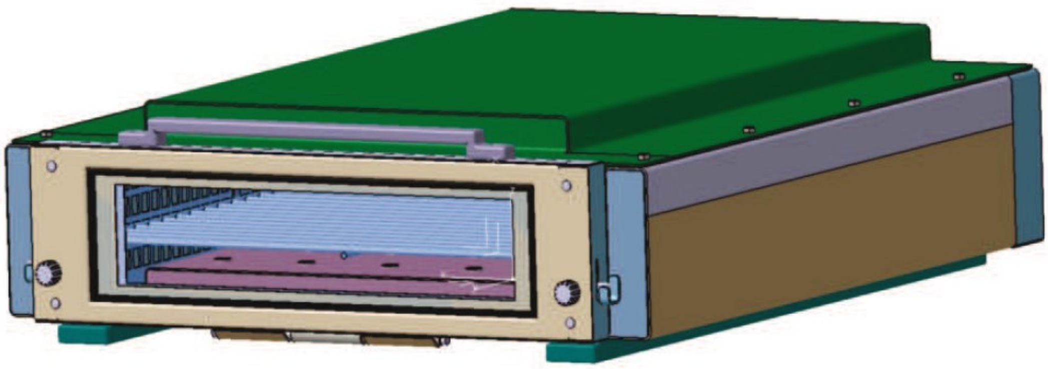


Fig. 11 Final design of air impingement prototype by Visentin (© courtesy of Alberto Visentin).

3.1.3 Description of the final air impingement prototype

In order to investigate the application of AI for thawing in food service, a new prototype (Fig. 12) was developed and assembled by Electrolux Professional Spa based on the research by Visentin (2018). Impingement thawing chamber (65 cm × 53 cm × 17 cm) and nozzles plate are shown in detail in Fig. 13. In particular, nozzle diameter was 1.2 cm with a pitch of 7.2 cm between each nozzle.

Fig. 12 Picture of the prototype and detail of the thawing chamber.

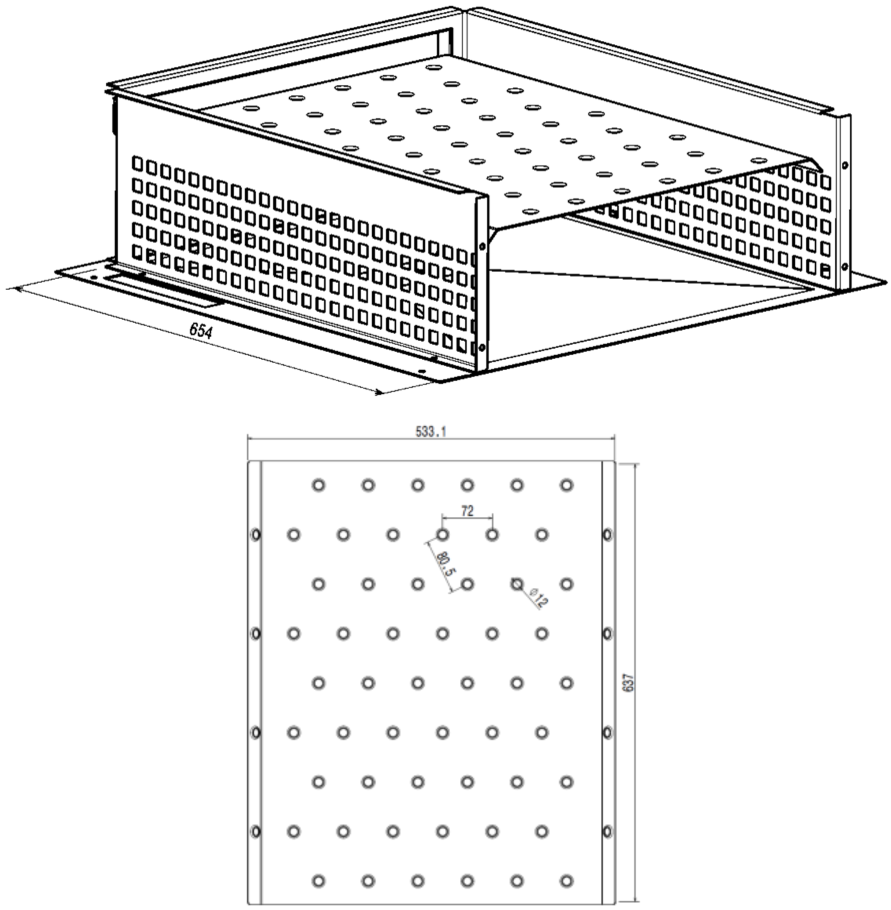
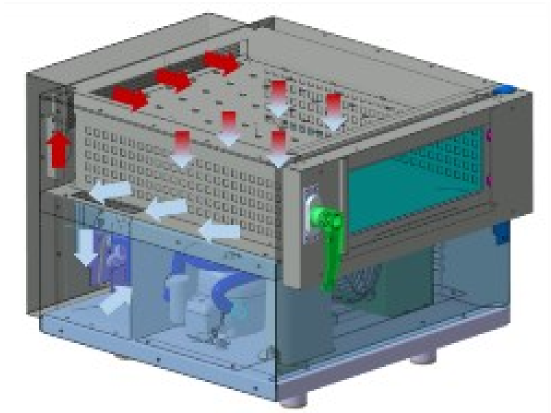


Fig. 13 Detail of air impingement prototype thawing chamber and nozzles plate (© courtesy of Emidio Tiberi).

In the impingement chamber inside the prototype, air jets from the nozzles impinge on the sample and then circulate in the exhaust outlets (Fig. 14). Recirculated air is filtered, and its temperature and speed are adjusted by a chiller, a blower and a heater. After passing the plenum, the air jets are sent again to the sample.



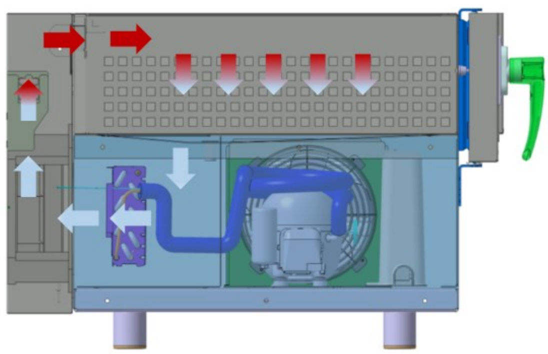


Fig. 14 CAD drawing and air flow recirculation scheme of the prototype (© courtesy of Emidio Tiberi).

Closed loop air circulation is provided by a centrifugal fan blower (backward curved type K3G250-RE07-07, Ebm-Papst Srl, Como, Italy) and air temperature is controlled by two tubular resistors heater (total power of 1.5 kW, IRCA SpA, Treviso, Italy) and a chiller (power rate 398 W 0/10 °C; R134a refrigerant; equipped with compressor EMT6170ZA CSIR 230V/50HZ power 1/3 hp by Embraco, Santa Catarina, Brasil). Polyuretan-polyester foam is used for the filter (10 pores-per-inch, 20-30 kg/m^3, Gomma Corvetto Srl, Monza, Italy). The prototype allows setting distance food to nozzles from 5.5 to 10.7 cm, air speed from 13.4 to 30.0 m/s, while air temperatures was used only in the range 4 - 15 °C (see section 1.5.1).

3.1.4 Conclusions

An AI thawing prototype was designed and assembled. Processing implications for QSR establishments (see section 1.5) of this thawing protype were considered of low impact. In fact, the AI thawing prototype requires no modifications of the outlet layout; moreover, thermal efficiency and geometric requirements intended for food service application were taken into account during the design phase, as well as production costs, in the view of a possible future industrialization of the product. Other processing implications, as noise production or ergonomics, were not evaluated on the prototype, however they were not expected to be critical in a final industrialized version.

3.2 – Definition of optimized air impingement thawing cycles.

To analyse the full potential of the AI thawing prototype described in chapter 3.1, the most promising cycles (combinations of process parameters) for AI thawing of chicken fingers had to be identified. The setup of food service processes is mostly based on professional expertise and on general considerations (i.e. to pursue "safe" temperature conditions). However, in the case of new applications - as AI thawing - when expertise has still to be developed, many trials are needed to identify the most promising combinations. This results in a considerable number of experiments and consequently high costs for companies. In addition, inadequate planning of the testing phase might lead to an underestimation of the potential of the new appliance. In engineering sector, an optimization approach can be applied to efficiently overcome these issues. This project, as mentioned in the preface, was carried out within a multidisciplinary research group, in interaction with engineers and mathematicians. In such context, knowledge and tools to employ an optimization approach and a thermal model simulating AI thawing were available. In this chapter, a novel optimization approach, specifically developed for this project, was presented in terms of its objectives and set up. Lastly, optimized air impingement thawing cycles chosen for this project were listed.

3.2.1 Optimization parameters and objectives

The objective of optimization problems is to improve one or more measured performances – the output variables – by adjusting the values of input variables (Muñoz, Sun, Kirkley, & Halgamuge, 2015). Core of an optimization approach is the availability of mathematical functions (called "objective functions") describing the output variables by varying input variables. The optimization algorithms then identify the combinations of input values leading to the best output value, e.g. the minimum or maximum of the functions. In our case, the input variables of the optimization problem were represented by thawing process parameters which can be set by the AI prototype operator. In detail, these parameters were the number of thawing stages and for each stage: duration, air temperature, air speed and distance of food to nozzles. Moreover, a computationally efficient version of Tiberi model (2018), describing the multiphase transient field inside a meat analogue during AI thawing, was available. Tiberi (2018) in his work defined three thawing performance indicators for AI thawing: thawing velocity, temperature uniformity in food volume and maximum temperature reached by the food. AI thermal model considered virtual frozen chicken fingers (in our case of 8 cm × 3 cm × 1.5 cm) as formed by small subunits (Fig. 15) and predicted the performance indicators on the basis of the input parameters. For this project, updated versions of these indicators were used as objective functions. The optimization problem target was to minimize them simultaneously. The objective functions were:

1) total time (hours) needed to reach 0 °C in all the virtual subunits of the sample;

2) temperature uniformity Indicator (UI) defined by Eq. 2, which is dimensionless and ranges from 0 (completely uniform) and 1;

$$(Eq. 2) \quad UI = \frac{1}{\Sigma_t} \int_t \frac{\int_V |T - \mu(T)| \, dV}{V \left(T_{tg} - T_0\right)} dt$$

Where T was the temperature of each sample subunit at time t, μ(T) is the average temperature of the food item of volume V at time t. T_0 is the food item initial temperature and T_{tg} is the target setpoint temperature 0 °C.

3) maximum local temperature within the food item reached during the process. This was kept as a general indicator that could be linked to temperature-induced spoilage phenomena, as the development of microbial flora or enzymatic activity.

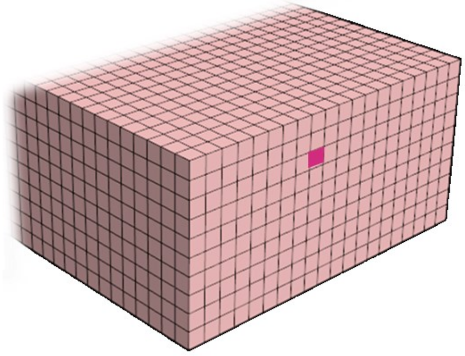


Fig. 15 Schematic representation of the virtual subunits of frozen chicken fingers (an example of single subunit is highlighted in dark pink) considered by the AI thawing thermal model.

A critical point had to be solved to apply an optimization approach to thawing. Which was the variation of physical behaviour of samples during the process, with a possible introduction of multimodal trends of the objective functions. The optimization algorithm had then to be robust without being deceived for examples by local minimums. For these purposes, an optimization approach to solve multi-objective optimization problems was developed by Pippia, Bozzato and Tiberi (2020).

3.2.2 Optimization method and set up

From an optimization point of view, the available AI thermal model can be considered as a black box function (Muñoz et al., 2015), because it cannot be expressed analytically, but only evaluated. A black box function can be directly solved applying the stochastic technique of genetic algorithms (Nguyen, Reiter & Rigo, 2014), to search a range of solutions that span the trade-off between each objective (Pareto front). Genetic algorithms (GA), are robust evolutionary algorithms, meaning that they are based on the Darwinian principle of survival of the fittest by maintaining a population of solutions of which the poorest are eliminated each generation (Holland, 1984; Goldberg & Holland, 1988; Evins 2013; Nguyen et al. 2014). The basic components of a GA are:

1. population: batch of solutions (combination of input parameters) currently under evaluation.
2. selection: selection of solutions to be recombined.
3. crossover: method of recombination of two solutions to obtain a new one.
4. mutation: introduction of a random alteration in a solution.

Genetic algorithm optimization (*gamultiobj*), already implemented in MATLAB R2019b (MathWorks Inc., Natick, Massachusetts), was used. This version allowed parallel computation, which was extremely helpful for time saving. A setup of the GA internal parameters was required, especially because a black box functions was considered. Taguchi design method was previously used for this purpose on single-objective optimization problems (Majumdar & Ghosh, 2015; Shavandia et al., 2012; Azadeh et al., 2017). This statistical method is largely used in Engineering to reduce the number of tests in a robust way. Moreover, it works with factors that have different number of levels. Pippia et al. (2020) demonstrated its efficiency for multi-objective problems using a hypervolume indicator - as described by Knowles, Thiele and Zitzler (2006) - to compare the results of different GA settings (Pareto fronts).

3.2.3 Optimized air impingement thawing cycles

The application of the optimization algorithm allowed obtaining a large set of optimal solutions (Pareto front), out of which nine possible combinations of process parameters (Table 2) were identified. These combinations (thawing cycles) were chosen to minimize the total thawing time (cycles A and B); to minimize food temperature and maximize its uniformity (cycles C, D and E); or as part of the intermediate zones of the Pareto front (cycles F, G, H and I). When possible, cycles aiming at the same object but with different number of stages were chosen. For instance, both cycles A and B allowed minimization of total thawing time, but this object was reached in one or two stages, respectively.

Table 2 Combinations of processing parameters (distance from food to nozzles, air temperature, air speed, stage duration) of each stage of the thawing cycles in the air impingement pilot equipment.

Thawing cycle	Distance food-nozzles (cm)	Air speed (m/s)	Stage 1		Stage 2		Stage 3	
			Air temperature (°C)	Time (min)	Air temperature (°C)	Time (min)	Air temperature (°C)	Time (min)
A	5.5	30.0	15	82				
B	5.5	23.1	15	68	10	22		
C	10.7	13.4	4	279				
D	5.5	14.3	7	14	4	222		
E	8.1	14.5	8	23	5	190		
F	10.7	24.9	13	46	10	49	9	22
G	5.5	24.3	12	50	8	68		
H	10.7	23.1	8	150				
I	8.1	29.0	11	44	8	82		

The cycles have a higher temperature in the first part to haste the process and lower temperature in the second part to maintain a better evenness. This sequence, is similar to the one reported for air thawing by James and James (2010), which includes an initial high temperature step above 10°C for 1 or 2 hours, to reduce the overall process duration, followed by a second step below 10°C to avoid excessive bacterial growth. It can be noted that, although five subsequent thawing steps were available, all defined cycles had up to three phases, suggesting that increasing the number of temperature steps may be not convenient to reduce the thawing time.

3.2.4 Conclusions

The set of the most promising air impingement thawing cycles (combinations of process parameters) for chicken fingers bags was identified by an optimization methodology. These cycles not only aimed at reducing total thawing time, but also at reducing temperature unevenness in the chicken fingers and reducing their local maximum temperature. In such way, risk of spoilage of food by temperature induced phenomena was reduced. Considering that the target study case – packaged chicken fingers – was not in direct contact with the thawing medium, also the risk of cross contamination was avoided. For these reasons, the use of the selected AI thawing cycles for chicken fingers was considered of low risk for food microbial safety. Albeit the optimization methodology required a tuning, the time spent in this operation was paid by an increase in optimization reliability and robustness. Moreover, nine AI thawing cycles were finally selected among hundreds of possible combinations in a relatively fast and cheap way.

3.3 – Validation of optimized air impingement thawing cycles.

In the previous section, nine AI thawing cycles for chicken fingers, to be applied in the prototype described in section 3.1, were identified by an optimization approach based on thawing modelling. Target of this part of the work was to validate the nine predicted thawing cycles, with the scope of supporting the abovementioned thawing model. To this end, the identified AI thawing cycles (Table 2) were applied on frozen chicken fingers to measure experimental values of thawing time and food temperature, to compare them with those predicted by the thawing model. Second target of this section was to compare the experimental thawing time of chicken fingers by the AI cycles with those resulting from refrigerator or microwave thawing. Hence, frozen chicken fingers were also thawed by these two methods for measuring thawing time and maximum reached temperature.

3.3.1 Materials and methods

Sample preparation

Chicken fingers (Fig. 16) of 8 × 3 × 1.5 cm were manually cut from fresh broiler breasts (P*ectoralis major*) purchased from a food service supplier (MARR SpA, Rimini, Italy). They were inserted in silicone molds (Silikomart Srl, Venezia, Italy) to prevent shape distortion, covered with PVC film, and individually frozen in a food service freezer (Prostore Premium, Electrolux Professional SpA, Italy) at -18 °C. Frozen chicken fingers were sealed with a vacuum sealer (EVP45, Electrolux Professional SpA, Italy) in polyethylene bags (20 × 30 cm; thickness 95 µm, Minipack-Torre SpA, Dalmine BG, Italy) and stored overnight at -18 °C.

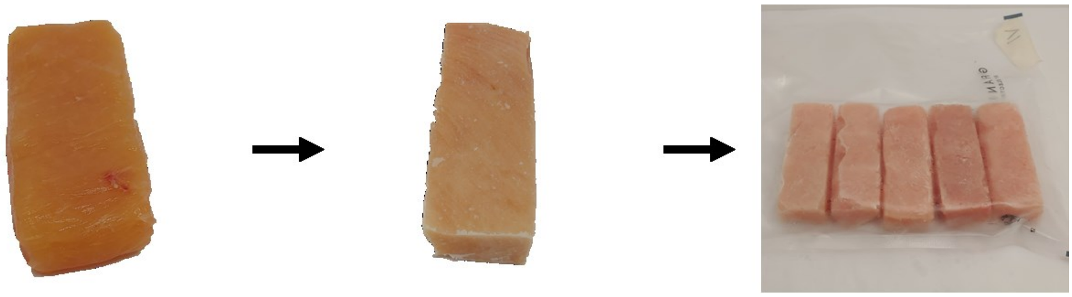


Fig. 16 Fresh, frozen and packed chicken fingers.

Thawing

Air impingement thawing

One bag of frozen chicken fingers was placed on a standard food service grid (GN 2/1, 53 × 65 cm). The bag was surrounded by frozen Tylose bricks (14 × 500 g, 20 × 10 × 2 cm), to simulate a complete load of a grid during a thawing cycle (Fig 17, top). The grid was inserted in the thawing chamber of the prototype AI thawing equipment (Fig. 17, bottom) described in chapter 3.1.3. Combinations of processing parameters for each thawing cycle were set as reported in Table 2. Activation of the power units of the prototype was recorded during the whole process by a logging software implemented in the prototype.

Refrigerator thawing

The grid loaded with chicken fingers and Tylose bricks was inserted in a food service refrigerator (Prostore Premium, Electrolux Professional SpA, Italy) at 4 ± 1°C.

Microwave thawing

A single bag of chicken fingers was placed inside a microwave oven (Mod. EVY7800ZOZ, Electrolux SpA, Stockholm, Sweden) at 100 W for 6 min.

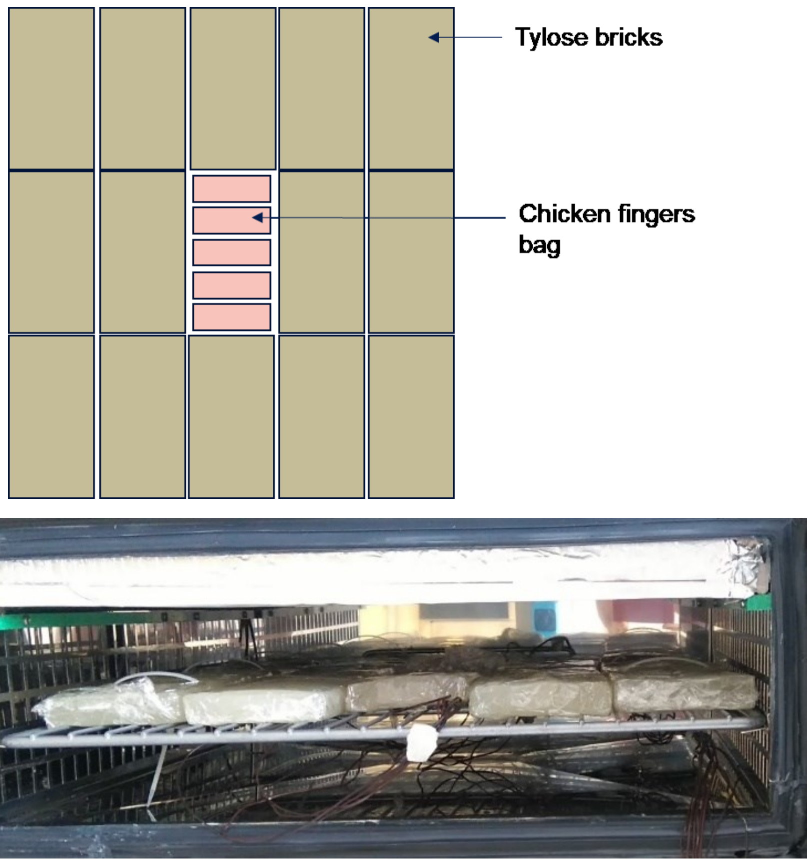


Fig. 17 Schematic representation of chicken fingers bag and Tylose bricks on grid (top) and grid loaded in air impingement prototype thawing chamber (bottom).

Temperature measurement

During AI and refrigerator thawing, sample temperature was monitored by T-type thermocouples (Tersid Srl, Milan, Italy) inserted in the central portion of the samples. For microwave thawing the temperature of the samples was monitored by T-type thermocouples (Tersid Srl, Milan, Italy) at the end of the thawing process. Data were recorded using a multimeter (Data logger 34972A with multiplex 34901A, Agilent, Santa Clara, California).

Maximum temperature and hot spots measurement

For each treatment, the maximum temperature reached by any thermocouple during thawing was considered the maximum local temperature of the product. For microwave thawing, the maximum was measured immediately after the thawing process in correspondence of hot spots.

Thawing time

Thawing time was measured as the time until all measured points of chicken fingers reached at least 0°C.

Statistical analysis

Results were presented as mean value ± standard deviation. Comparison of results was performed using R 4.0.2 software (R Foundation for Statistical Computing, Vienna, Austria). Shapiro-Wilk test for normality and Bartlett test for homoscedasticity were applied. Depending on the result, parametric or non-parametric tests were used. For comparison of two data sets t-test or Wilcoxon rank sum test were used, for more data sets ANOVA and Tukey multiple comparison of means, or non-parametric Kruskal-Wallis test and Wilcoxon rank sum test were performed. Significance level was set to $p < 0.05$. Correlation analysis was performed using Excel 365 (Microsoft Corporation, Redmond, Washington).

3.3.2 Results and Discussion

AI thawing cycles identified by optimization (Table 2) were applied on frozen chicken fingers in the AI prototype. Experimental values of thawing time (minimum food temperature 0 °C) and maximum local temperature of chicken fingers were reported in Table 3, juxtaposed to values predicted based on model estimation. Figure 18 shows an example of the experimental and modelled temperature profiles. Temperature uniformity was not experimentally assessed because of the difficulty of placing numerous thermocouples within a single chicken finger without affecting thermal process and reliability of temperature measurement. Data relevant to chicken fingers thawed in refrigerator or in a microwave's oven, are also shown in Table 3. For microwave thawing, a previously defined fixed thawing time was applied.

Table 3 Experimental and predicted values of thawing time and maximum temperature of chicken fingers thawed by air impingement thawing according to different cycles. Control data, relevant to chicken fingers thawed in a refrigerator at 4 ± 1 °C and by microwaves, are also shown.

Thawing cycle	Thawing time (min)		Maximum temperature (°C)	
	Predicted	Experimental	Predicted	Experimental
A	82	85 ± 6	10.7	7.5 ± 1.0
B	90	92 ± 8	7.5	6.0 ± 1.0
C	279	262 ± 1	2.6	3.4 ± 1.0
D	238	257 ± 15	3.4	3.5 ± 1.0
E	180	136 ± 1	0.8	0.2 ± 1.0
F	117	157 ± 17	8.2	7.3 ± 1.0
G	118	98 ± 7	6.6	6.1 ± 1.0
H	150	188 ± 5	7.5	7.8 ± 1.0
I	126	126 ± 1	5.8	5.0 ± 1.0
Refrigerator	ND	600 ± 37	ND	4.0 ± 1.0
Microwaves	ND	6	ND	45.0 ± 5.0

Correlation analysis of experimental and predicted thawing time for the AI thawing cycles was performed. The result showed a good agreement ($r = 0.91$, $p < 0.01$), even though the thermal model doesn't consider mass transfers. The reason could be addressed to the use of PE bags during the tests, hindering the evaporation processes. Moreover, the maximum temperature reached by chicken fingers during thawing was comparable or lower than the predicted values. Observed differences can be attributed to positioning of temperature sensors within the sample and intrinsic variability of the food matrix, in particular anisotropy of the material leading to preferential heat conduction directions inside meat structure. These results support the thermal model of AI thawing used in the optimization process. Table 3 also shows, as expected, that the longest chicken fingers thawing time was measured for refrigerator thawing. The application of AI noticeably reduced thawing time, corresponding to a reduction of 56 to 85% as compared to refrigerator method. It is worth noting that, when thawing was performed at the same temperature applied in the refrigerator (4 °C) but with the assistance of AI (cycle C) even at the lowest air speed (13.4 m/s), thawing time was more than halved, confirming the heat exchange efficiency of AI. This result is particularly interesting because shorter thawing times could allow more loads of frozen food a day, improving the flexibility of use and reducing the space consumption for the thawing processes. Microwave thawing further reduced thawing time as compared to refrigerator method, however, hot spots were observed on the product, locally reaching up to 45 °C (Fig. 19). Considering the increase in temperature, it is possible that if microwaved products are not immediately used, a microbiological risk may arise. In addition, it is worth mentioning that microwave ovens are usually small and also in this case the quantity of thawed product was much smaller (0.2 kg) as compared to the other two methods (7.2 kg considering the food simulant). In fact, increasing the load of the microwave decreases food quality by even more critical formation of hot spots (data not presented) and thawing time is also increased. Consequently, as shown in Table 4, the load of chicken fingers thawed in 10 hours (refrigerator thawing time) by microwaves result smaller than the one thawed by most of the AI thawing cycles. Moreover, more work by operators is needed for the loading and unloading steps.

Table 4 Calculated number of complete thawing cycles performed in ten hours and quantity of chicken fingers thawed for air impingement, refrigerator and microwave thawing.

Thawing cycle	Number of thawing cycles completed in 10 hours	Chicken fingers thawed (kg/10 h)
A	7	50.4
B	6	43.2
C	2	14.4
D	2	14.4
E	4	28.8
F	3	21.6
G	6	43.2
H	3	21.6
I	4	28.8
Refrigerator	1	7.2
Microwaves	100	20.0

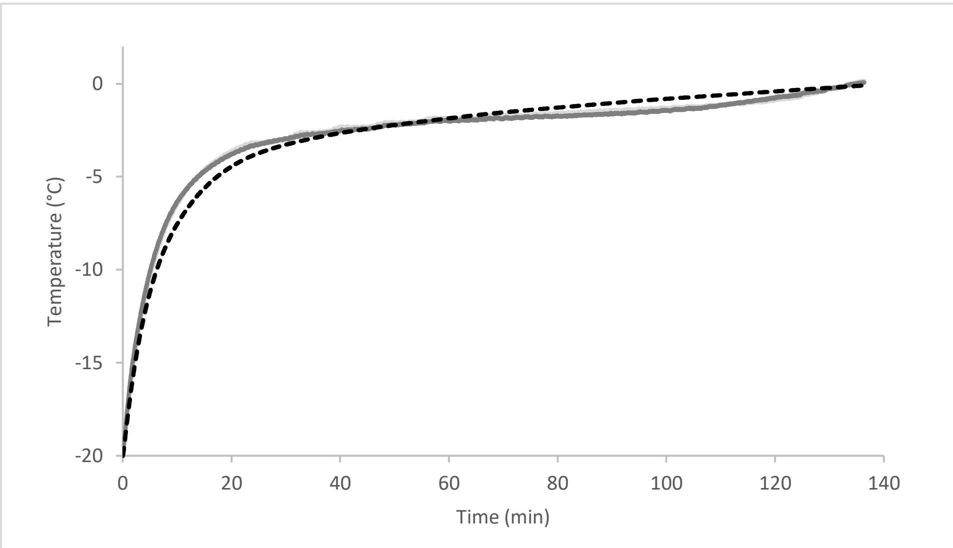


Fig. 18 Model predicted (black dotted line) and experimental (grey continuous lines) temperatures of chicken fingers during air impingement thawing.

Fig. 19 Microwave thawed chicken fingers with hot spots, top and bottom view.

3.3.3 Conclusions

Although small deviations were observed, experimental thawing time and maximum food temperature of AI thawed chicken fingers were in good agreement with those predicted by the thawing model, supporting its validity. In addition, experimental data demonstrated that, as compared to refrigerator thawing, the application of AI drastically reduced thawing time of chicken fingers (by 56 to 85%). Even though microwave thawing was the fastest thawing method, its productivity calculated over ten hours (refrigerator thawing time for chicken fingers) was smaller than most of the AI thawing cycles, as a smaller load could fit into the oven cavity. In addition, a bigger effort for loading and unloading operations is required. Lastly, development of hot spots was observed on microwave thawed chicken fingers, while no evident deterioration of AI thawed samples was observed. All these results suggest that AI thawing could represent an interesting alternative for improving QSR thawing process, further motivating the need for a deeper evaluation of the effects of AI thawing on food quality in comparison with refrigerator method.

3.4 – Performances of air impingement thawed chicken fingers.

Application of AI thawing cycles identified in 3.2 allowed a relevant reduction of chicken fingers thawing time in comparison with refrigerator thawing. This reduction was the result of the application of process parameters which differed for each cycle. It is then possible that the selection of a specific thawing cycle could determine not negligible changes in chicken tissue (as described in section 1.3). In other words, even though AI thawed samples were not noticeably affected by thawing, as occurred upon microwave thawing, reduction of thawing time could have caused unpredictable modifications on meat tissue and protein structure as compared to refrigerator thawing, possibly affecting thawing yield. Consequently, a comparison of the chicken fingers performances upon application of the different thawing cycles was performed. Thawing loss, thawing rate and WHC were firstly analysed for all nine AI thawing cycles and compared to refrigerator and microwave thawed samples. Successively firmness, microstructure and FTIR spectra of chicken fingers thawed by the three most interesting AI thawing cycles were compared with those of fresh, frozen and refrigerator thawed samples.

3.4.1 Materials and methods

Experimental plan

Frozen chicken fingers, thawed by air impingement, refrigerator and microwaves as described in chapter 3.3, were analysed as shown in experimental plan in Fig. 20. Statistical analysis was performed as described in chapter 3.3.

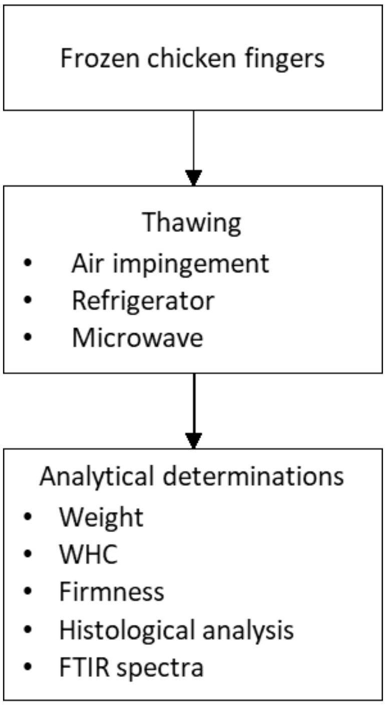


Fig. 20 Experimental plan to evaluate the effect of the thawing method on chicken fingers.

Thawing rate

Thawing rate was calculated as the time needed to cross the temperature zone of maximum phase transition which, according to the literature, occurs between 0 and -5 °C (Farid 2002; Kono, Kon, Araki, & Sagara, 2017).

Thawing loss

Thawed samples were weighted (scale PKS 200-3 Kern-Sohn, Belingen, Germany) after gentle blotting with cellulose paper, in order to take into account all the drip. Thawing loss was determined, according to Eq. (3), by weighting frozen and thawed samples. For each sample at least six measures were performed.

$$(Eq\ 3)\ Thawing\ loss\ (\%) = \frac{Mass\ after\ freezing - Mass\ after\ thawing}{Mass\ after\ freezing} \times 100\%$$

Water Holding Capacity

Water holding capacity (WHC) of chicken fingers was determined by filter paper press method (Grau & Hamm, 1953). Cubes of 0.3 g (with edges of circa 0.6 cm) were manually cut with a sharp knife from the chicken finger internal portion, always from the same positions. Each cube was placed onto a square of 7 × 7 cm of filter paper (Whatman No. 1/2) and pressed for 5 min between two plexiglass plates with a load of 10 kg. WHC was calculated as percentage ratio between area of pressed sample and area of water stain on filter paper. Areas were measured by image analysis using MATLAB R2017b (MathWorks Inc., Natick, Massachusetts). At least fifteen measures were performed for each treatment.

Firmness

A Warner-Bratzler (V-notch) blade attached to an Instron 4301 (Instron Ltd, High Wycombe, UK) was used to measure the firmness of samples. Chicken fingers were cut parallel to muscle fibres, always in the same position, for a total of five measures for each replicate. Firmness was defined as the shear force (N) required to cut the samples. Test speed was 100 mm/min. Software Automated Materials Testing System was used for the analysis (version 5, series IX, Instron LTD, High Wycombe, UK).

Histological analysis

A microtome blade was used to cut meat cubes (edges of circa 1 cm) from the internal portions of chicken fingers, always from the same position. Cubes cut from fresh, frozen and thawed chicken fingers were then fixed by immersion in Bouin solution (Sigma Aldrich, St. Louis, MO, USA). After fixation, samples were processed by an automatic histoprocessor (TISBE tissue processor, Diapath, Martinego, Italy) and embed in paraffin (ParaplastPlus, Diapath, Martinego, Italy). Sections, cut with a programmable microtome (RM2135, Leica, Wetzlar, Germany), were dewaxed, stained with Mayer's haematoxylin and eosin (Sigma Aldrich, St. Louis, MO, USA) and examined using an optical microscope (DMRB, Leitz, Stuttgart, Germany). For each sample at least three 10× images were acquired and analysed by NIS-Elements BR software (version 5.11.00, Nikon, Tokyo, Japan). Intercellular area was identified as Region of Interest (ROI) by selection of not-stained pixels and its value was calculated as percentage ratio on total picture area (Eq. 4).

$$(Eq\ 4)\ \text{Intercellular area}\ (\%) = \frac{Area\ of\ ROI}{Area\ of\ micrograph} \times 100$$

FT-IR spectroscopy

Fresh or thawed chicken fingers were inserted in 50 ml polypropylene centrifuge tubes and centrifuged at 15,000 × g for 15 min at 4 °C, as described by Grunert, Stephan, Ehling-Schulz and Johler (2016). 20 µl of the press-juice were spotted on the ATR (Attenuated Total Reflection) crystal of a FTIR spectrometer (Alpha-P, Bruker, Massachusetts, USA). Spectral acquisition in transmission mode was performed in the spectral range of 4,000 to 400 cm^{-1}. Averages of at least three spectra for each treatment and their second derivative (9-point Savitzky-Golay filter) were normalized and compared using OPUS 6.5 software (Bruker, Billerica, USA).

3.4.2 Results and discussion

Thawing loss and WHC of the thawed chicken fingers are reported in Table 5. Thawing rate was also calculated as an index of heat transfer efficacy for AI and refrigerator thawed samples. Thawing loss of all thawing cycles, comprising refrigerator and microwave thawing, resulted to be comparable ($p > 0.05$). As for microwaves, it is possible that the observed damage of tissue (hot spots) didn't result in thawing losses as only a portion of the samples was affected and secondarily because the weight was measured immediately after the thawing process. Possibly, a rest phase would have permitted to meat enzymes to affect the tissues resulting in higher thawing loss. Correlation analysis indicated that there was no relation between thawing loss and thawing rate for AI and refrigerator thawing ($p > 0.05$). It was hypothesised that, for these two thawing methods, the effects of slow and fast thawing described in section 1.3 were counterbalanced on the maintenance of the original tissue structure. This result was particularly positive for the targets of this project, as meat thawing can be performed in shorter time without affecting the overall process yield and thus food product economic value (James & James, 2010; Bedane, Altin, Erol, Marra, & Erdogdu, 2018). WHC of thawed samples, the ability of the tissue to retain original moisture, was compared to further evaluate indirectly their meat structure (see section 1.3). Even though AI thawing cycles A, G and I showed higher WHC values ($p < 0.05$) than cycle F, WHC values of AI, refrigerator and microwave thawed samples were comparable ($p > 0.05$). However, microwave thawing showed a larger standard deviation of WHC as compared to other thawing methods, due to the presence of hot spots. A correlation analysis indicated that for AI and refrigerator thawing, no relation ($p > 0.05$) was present between WHC and thawing rate, consistently with thawing loss results.

Table 5 Thawing loss, thawing rate and WHC of chicken fingers thawed using different cycles of air impingement (AI). Control data, relevant to chicken fingers thawed in a refrigerator and with microwaves, are also shown.

Thawing cycle	Thawing loss (%)	Thawing rate (°C/min)	WHC (%)
A	2.3 ± 0.5[a]	0.10 ± 0.01[a]	22.9 ± 2.2 [a]
B	3.2 ± 1.0[a]	0.12 ± 0.01[a]	21.7± 3.2 [ab]
C	2.0 ± 0.4[a]	0.02 ± 0.01[a]	21.9 ± 2.7 [ab]
D	3.4 ± 1.1[a]	0.03 ± 0.01[a]	21.1 ± 2.5 [ab]
E	2.5 ± 0.8[a]	0.04 ± 0.01[a]	21.7 ± 2.9 [ab]
F	2.5 ± 1.0[a]	0.06 ± 0.02[a]	19.0 ± 2.7 [b]
G	2.6 ± 0.8[a]	0.10 ± 0.03[a]	23.4 ± 2.1 [a]
H	3.3 ± 0.4[a]	0.04 ± 0.01[a]	21.2 ± 2.9 [ab]
I	2.8 ± 1.1[a]	0.10 ± 0.04[a]	23.3 ± 3.3 [a]
Refrigerator	3.9 ± 1.2[a]	0.01 ± 0.01[a]	20.6 ± 3.3 [ab]
Microwaves	3.0 ± 1.0[a]	NA	21.5 ± 7.2[ab]

[a,b] for each property, means indicated by the same letter are not significantly different ($p > 0.05$); NA = not available.

Firmness, microstructure and FTIR spectra analysis of a more limited number of AI thawing cycles was performed. In particular, cycle A was selected for being the fastest (85 min); cycle E was chosen for leading to the minimum temperature increase in food (0.2 °C); cycle H was identified as representative of cycles of the intermediate zones of the Pareto front (see section 3.2). Firmness values of thawed samples were reported in Table 6. Results were compared to those relevant to fresh, frozen and refrigerator or microwave thawed samples.

Table 6 Firmness of fresh and differently thawed chicken fingers.

Sample	Firmness (N)
Fresh	21.3 ± 2.9 [a]
AI cycle A thawed	21.6 ± 1.8 [a]
AI cycle E thawed	21.0 ± 1.8 [a]
AI cycle H thawed	21.8 ± 1.7 [a]
Refrigerator thawed	23.4 ± 2.1 [a]
Microwave thawed	22.4 ± 5.5 [a]

[a] *for each property, means indicated by the same letter are not significantly different ($p > 0.05$).*

Even though firmness of all samples was comparable ($p > 0.05$), a higher standard deviation was observed, as expected, for microwaved samples due to the local presence of hot spots. To evaluate if unnoticeable differences were present between samples thawed by different AI cycles and refrigerator, histological and FTIR spectral analysis were performed. In fact, regardless of comparable firmness, interesting differences were observed in the micrographs (Fig. 21). Fresh chicken fingers muscle fibres were, compact and well-organized; extremely fine cracks observed were imputed to artifacts (Ishiguro & Horimizu, 2008). Dissimilarly, the formation of big ice crystals in frozen meat was reflected in tissue damage as indicated by the deformation of cell shape. After thawing, muscle fibres recovered part of their volume because of the inflow of water. However, gaps were still present between fibres, reasonably consequence of the formation of extra-cellular ice crystals and separation of connective tissues from the muscle fibres. Fine cracks observed in the fibres of thawed samples might be attributed to intracellular freezing damage, as described by Ishiguro & Horimizu (2008). As compared to other thawed samples, chicken fingers thawed by cycle E presented smaller gaps between fibres and a lower number of visibly damaged cells. In order to verify this observation, image analysis was performed to calculate intercellular areas in the micrographs (Table 7). Data confirmed that intracellular area of AI cycle E thawed samples was significantly smaller than those associated to other thawing cycles ($p < 0.05$) and comparable to that of fresh meat. Conversely, intracellular areas of other thawing cycles resulted comparable to that of frozen samples. These results suggest that minimization of sample temperature, as occurs upon cycle E, could retain more efficiently original structure of meat.

Table 7 Intercellular area of fresh, frozen and differently thawed chicken fingers.

Sample	Intercellular area (%)
Fresh	11.9 ± 0.5 [b]
Frozen	39.7 ± 4.5 [a]
Refrigerator thawed	27.2 ± 6.8 [a]
Cycle A thawed	35.4 ± 4.7 [a]
Cycle E thawed	14.9 ± 0.3 [b]
Cycle H thawed	23.1 ± 1.0 [a]

[a,b] *for each property, means indicated by the same letter are not significantly different ($p > 0.05$).*

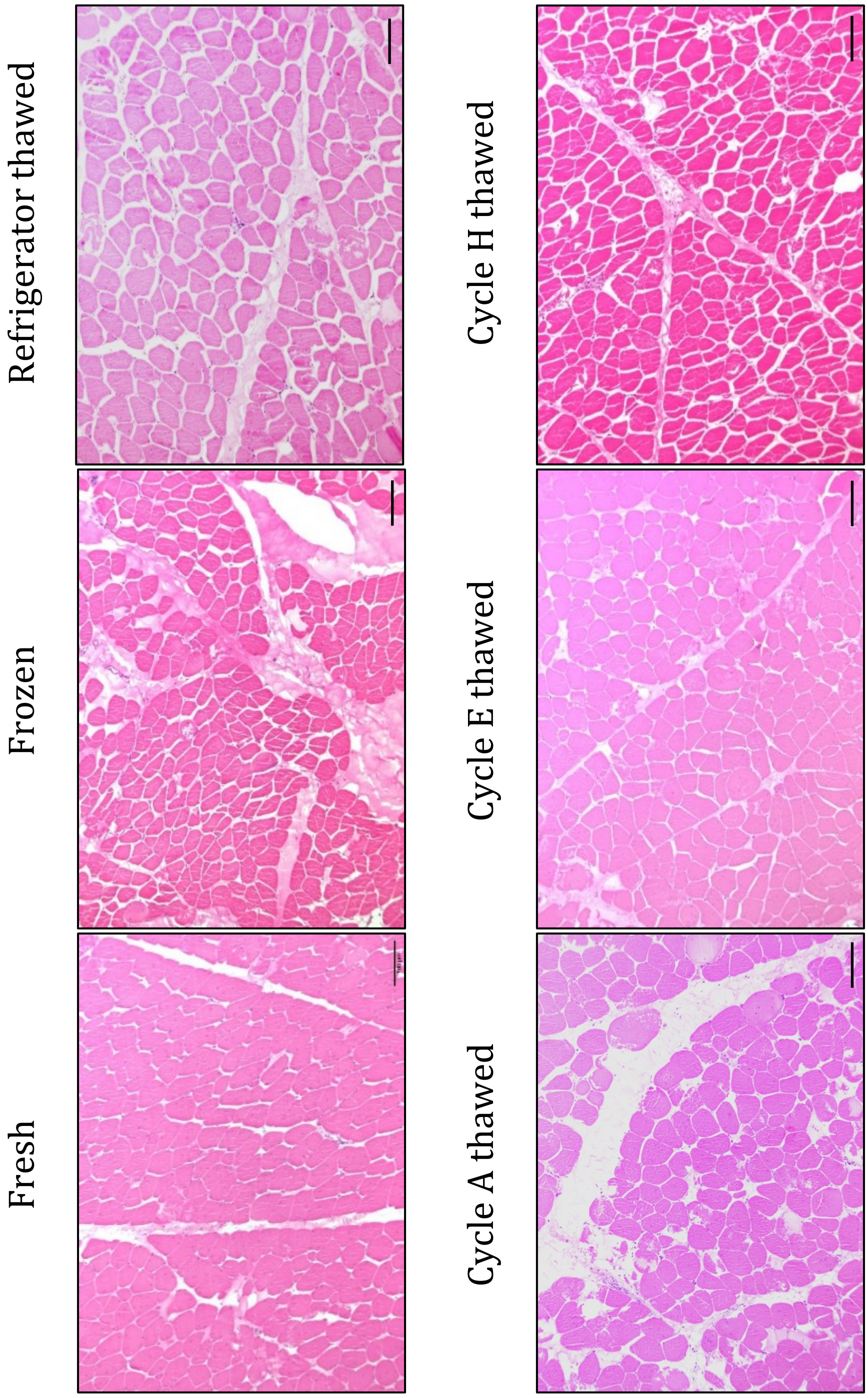


Fig. 21 Micrographs (black scale bar equal to 100 μm) of fresh, frozen and differently thawed chicken fingers.

FTIR spectral evaluation of fresh and AI or refrigerator thawed chicken finger was performed. All FTIR spectra (Fig. 22) showed bands associable to amide I and II (1500-1700 cm^{-1}) and to alcoholic hydroxyl group (around 3300 cm^{-1}). Second derivative of the Amide I range (1600-1700 cm^{-1}) (Fig. 23) showed the typical bands associated to β-sheet at 1624 cm^{-1} and 1633 cm^{-1}, random coil at 1646 cm^{-1}, α-helix between 1654-1658 cm^{-1}, 3_{10}-helices at 1663 cm^{-1} and β-turn at 1675 and 1688 cm^{-1} compatible with previous data for proteins secondary structures in water media (Kong & Yu, 2007). Slight changes between β-turn and 3_{10}-helices band spectra were observed for thawed samples as compared to the unfrozen sample (Fig. 24). These findings may be indicative for changes in the protein secondary structure and are partially in line with observations of Grunert et al. (2016), who observed maximum differences between fresh thawed chicken breast samples II derivatives in the 1628-1660 cm^{-1} spectral window. It can be noted that, in this wavelength region, spectra of meat thawed by AI cycle E resembled that of fresh meat more closely than other cycles, with minor differences in other bands. This result was in line with the findings of the microstructure of the thawed samples.

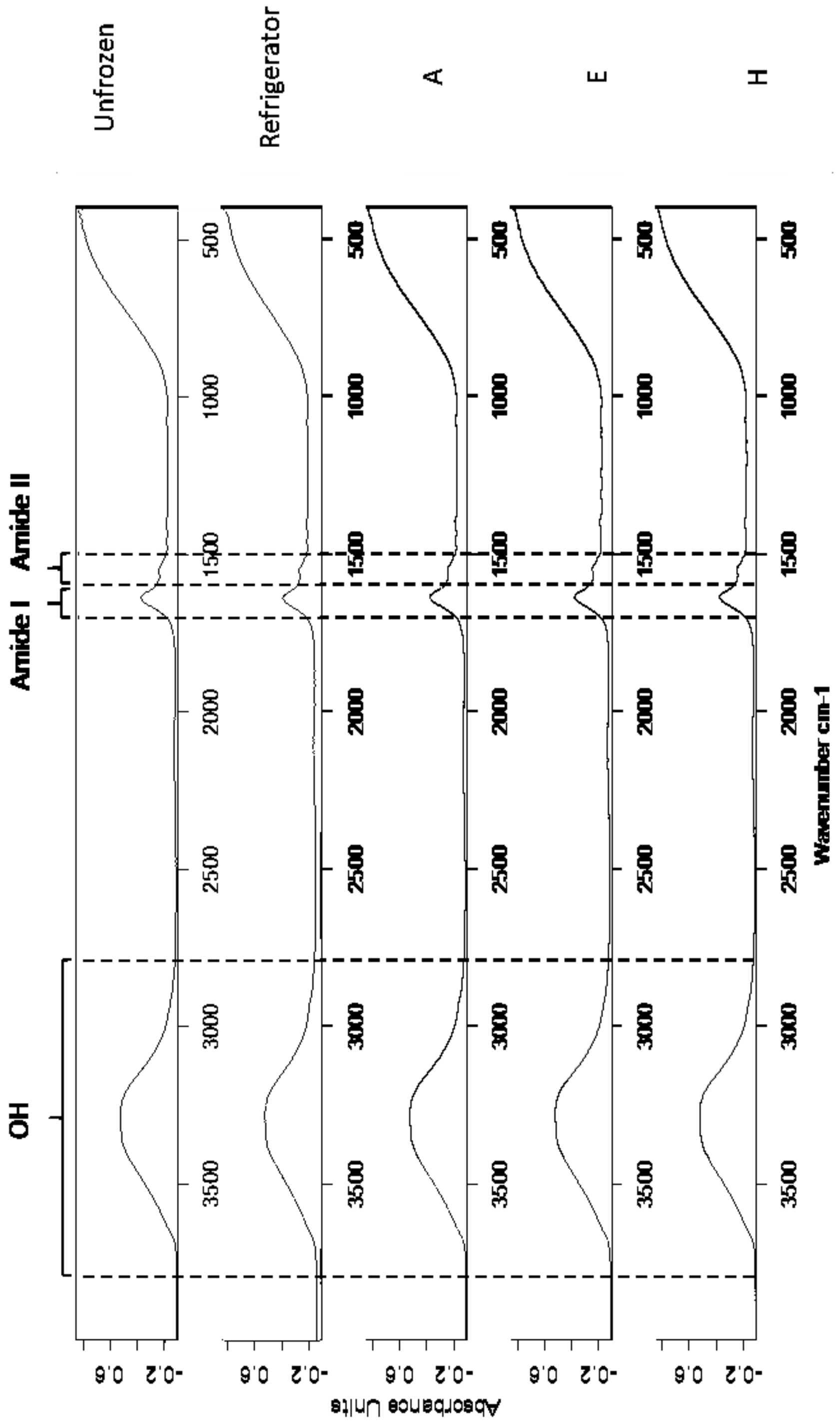


Fig. 22 FTIR spectra 400 – 4000 cm-1 of chicken fingers: fresh unfrozen, refrigerator thawed, and AI thawed by cycles A, E, H.

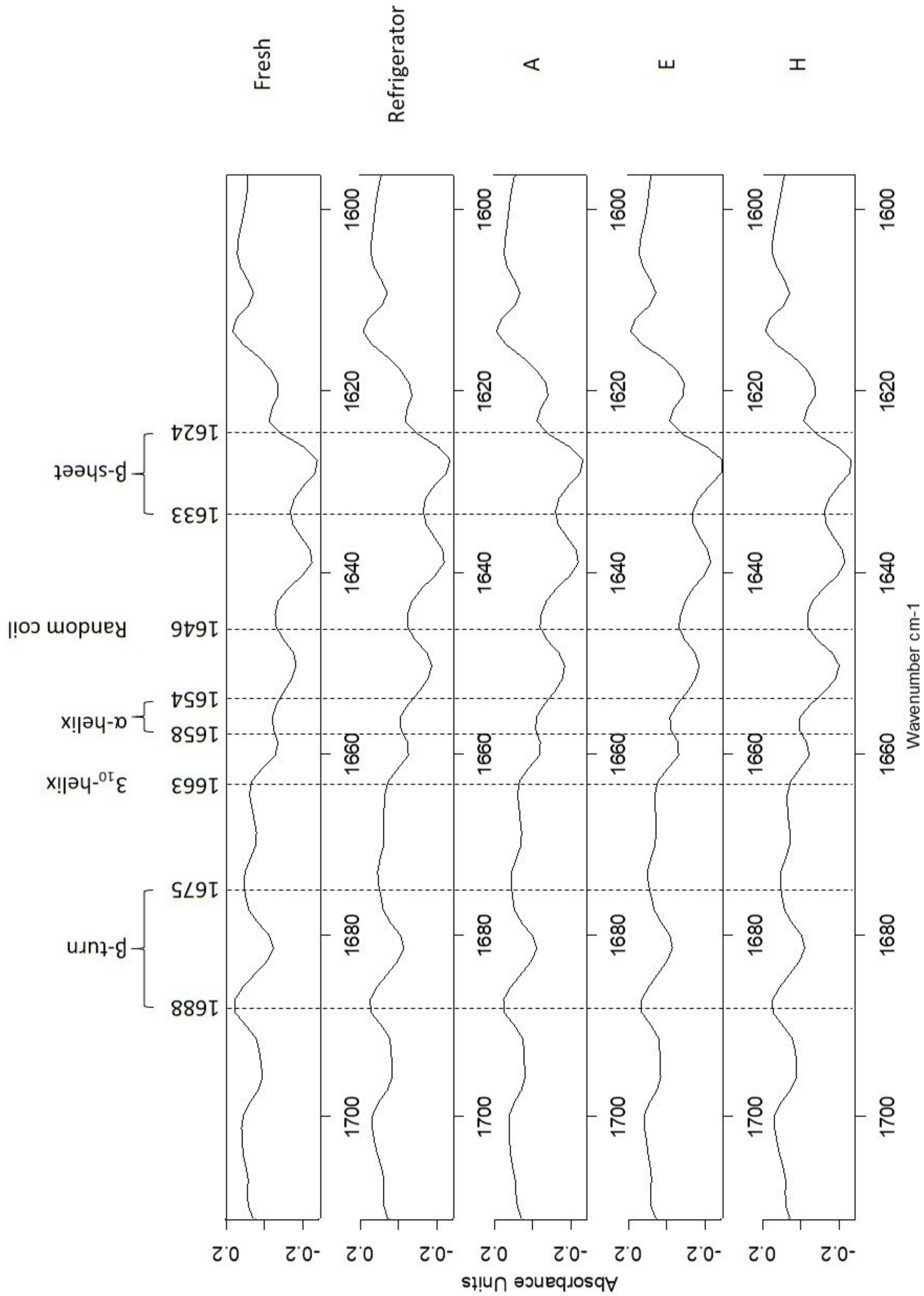


Fig. 23 FTIR spectra second derivative of the Amide I band of chicken fingers: fresh unfrozen, refrigerator thawed, and AI thawed by cycles A, E, H.

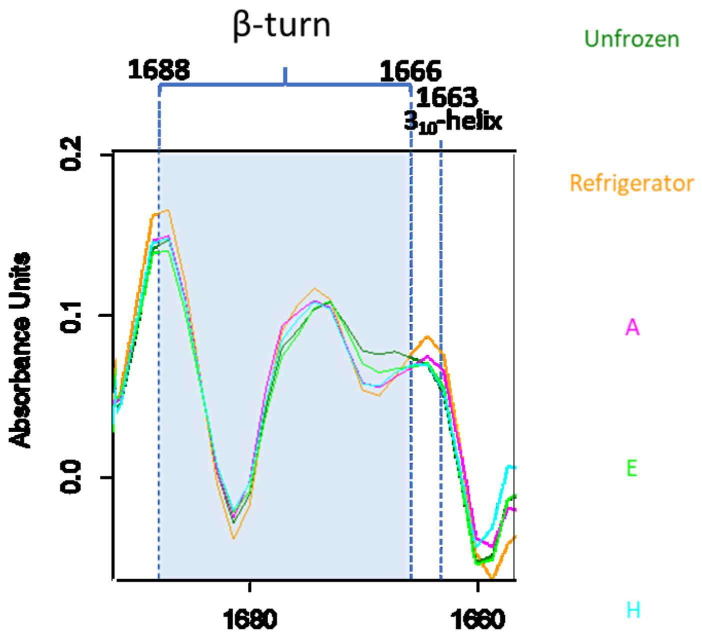


Fig. 24 Detail of the FTIR spectra second derivative of the Amide I band of chicken fingers. Computer-aided superimposition of spectra by fresh unfrozen, refrigerator thawed, and AI thawed by cycles A, E, H.

3.4.3 Conclusions

Reduction of the thawing time for chicken fingers, previously observed for all AI thawing cycles, was not associated with a deterioration of thawing loss or WHC of the meat as compared to control refrigerator thawing. The unvaried food yield after thawing supports the utilization of AI as alternative thawing method for QSR (see criteria in section 1.5), even though yield after cooking should also be analysed. In addition, firmness, histological analysis and FTIR amide spectra of all selected AI thawed samples did not indicate any impairment of chicken fingers microstructure as compared to refrigerated ones. On the contrary, one of the AI thawing cycles – chosen for the low temperature increase of food – showed promising results in maintaining the structure of the original fresh meat. Even though preservation of the original structure is a positive result for a thawing process, in our case the focus was on food service application of AI thawing method. Hence, it was chosen to perform further trials using this AI thawing cycle (cycle E, Table 2) to investigate if the observed differences affected the final fried product. On a side note, microwave thawing didn't affect in significative way the average values of thawing losses, WHC or firmness, but an increase of standard deviation was observed for WHC and firmness, due to the local hot spots.

3.5 – Performances upon frying of air impingement thawed chicken fingers.

Chicken fingers thawed by AI while minimizing food local temperature (cycle E, Table 2) showed a better preservation of meat original structure in comparison to refrigerator thawed samples. As noted in section 1.4, performances of food upon frying are strictly dependant on its structure. It is thus possible that the structural differences observed in the chicken fingers may affect their performances upon frying. Target of this section was to elucidate if the application of AI while minimizing food local temperature, as compared to refrigerator thawing, resulted in significative differences on fried chicken fingers quality. Microwave thawing was also applied to verify if the observed hot spots formed during thawing affected fried food performances perceptibly. In particular, quality criteria sought in fried food by customers (see section 1.4) were considered. Hence in this chapter, chicken fingers were thawed by the abovementioned AI cycle "E", by refrigerator or by microwaves, analysed for their colour parameters, coated with a commercial breading mixture, fried and compared in terms of cooking loss, firmness, moisture loss, fat uptake, colour and by sensorial analysis. In addition, an estimation of caloric reduction and fat savings due to different average fat uptake was performed.

3.5.1 Materials and methods

Experimental plans

Frozen chicken fingers were thawed by refrigerator, microwaves or air impingement cycle E (Table 2) as described in chapter 3.3, breaded, fried and analysed according to experimental plan in Fig. 25. Statistical analysis was performed as described in section 3.3.

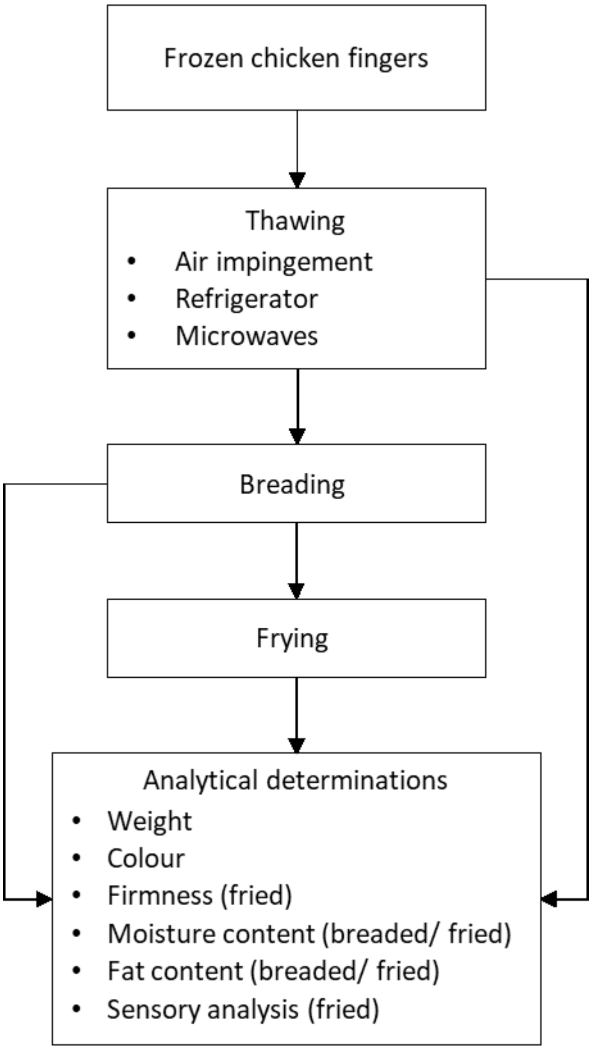


Fig. 25 Experimental plan to evaluate the effect of the thawing method on fried chicken fingers.

Colour

L*, a*, b* colour parameters of thawed or fried food samples were measured using a CR-400 colour meter (Konica Minolta, Tokyo, Japan) with measuring head CR-A33, C illuminant and 2 degrees observer. For each sample 30 measures were performed. Colour measurement was performed on samples at room temperature.

Breading

Chicken fingers were quickly soaked in cold water (17 °C) and manually breaded (Fig. 26, left) with a breading mix (*) (Impan, Ariosto SpA, Buccinasco, Italy). Breading excess was removed by placing chicken fingers in a sieve (1.75×10^{-3} cm) and shaking the product.

(*) Ingredients: Breadcrumbs (soft wheat flour type “0”, brewer’s yeast, salt), soft wheat flour type “0”, powdered egg (8%), salt, sweet paprika powder.

Frying

Each breaded sample was fried for 4.5 min at 190°C in a tabletop fryer (Tefal F63-M1, Rumilly, France) filled with 2.8 L of sunflower oil (DAC SpA, Flero, Italy). Frying oil was changed after each cooking test. After frying, samples (Fig. 26, right) were drained shaking the frying basket and put on fat absorbing paper for restaurants. Samples were blotted for 3 seconds for each side. Samples were then placed on griddles to cool down at room temperature for circa 45 minutes.

Fig. 26 Coated (left) and fried (right) chicken fingers.

Cooking loss

Cooking loss was determined according to Eq. (5), weighting (scale PKS 200-3 Kern-Sohn, Belingen, Germany) samples after breading and after frying. For each treatment at least twenty measures were performed.

$$(Eq\ 5)\ Cooking\ loss\ (\%) = \frac{Weight\ after\ breading\ -\ Weight\ after\ frying}{Weight\ after\ breading} \times 100\%$$

Firmness

Firmness was measured as described in section 3.4 on refrigerated fried chicken fingers, using a test speed of 60 mm/min.

Moisture loss

Dry matter of breaded or fried samples was determined by weighting the sample (scale Rad Wag AS220/C/2) before and after freeze-drying (Mini Fast 1700, Edwards Alto Vuoto, Milan, Italy). For the latter, capacitors were set at -40 / 45 °C and the plates at -20 °C. Moisture loss, expressed as mass of moisture in 100 g, was calculated according to Eq. (6).

$$(Eq. 6)\ Moisture\ loss = \%\ Moisture(fried\ sample) - \%\ Moisture(breaded\ sample)$$

Fat uptake

Freeze-dried samples were minced with a food processor (Moulinex MC300132) at maximum speed level for 45 s. Aliquots of 2.5 g were inserted in the Sohxlet extractor (Solvent Extraction VELP SER 148) with petroleum ether. Extraction parameters were 30 min immersion, 1 h washing, 40 min di evaporation and cooling water flux was set at 5 L/min. After stabilization under hood for 2 h, samples were weighted. Fat uptake, expressed as mass of fat in 100 g dry matter, was calculated according to Eq. (7).

$$(Eq. 7)\ Fat\ uptake\ = \%\ Fat(fried\ sample) - \%\ Fat(breaded\ sample)$$

Sensory analysis

Untrained panelists (n = 24, age between 25 and 55 years) were recruited in Electrolux Professional's research and development department. Each panelist was provided with a plastic plate with two halves of just fried chicken fingers, one codified with a three-digit number and one with the "R" (reference) letter. The "R" control was attributed the central point, equivalent to 3.5 cm, on 7 cm unstructured line scales for four quality parameters: browning, visible greasiness, crunchiness and meat firmness (Annex A). Panelists were instructed to compare the three-digit coded sample (refrigerator, AI or microwave thawed-fried chicken finger half) to the "R" control (refrigerator thawed-fried chicken finger half) and indicate the perceived intensity of the quality parameters. Each panelist evaluated all samples, and all combinations of order of presentation of the differently thawed samples were evenly assigned. Evaluation experiments were performed on three days, in separate desks with no additional interference factors, and water was provided for mouth rinsing between reference and sample. At the end of the experiments, distances of the assigned scores from the left-end of the lines were measured and used to perform the statistical analysis.

3.5.2 Results and discussion

Chicken fingers were thawed by refrigerator, microwaves or air impingement (Table 2, cycle E). Colour parameters (L^*, a^*, b^*) of the thawed chicken fingers were compared (Table 8). Microwave thawed chicken fingers, as expected, showed the highest ($p < 0.05$) luminosity (L^*) and lowest redness (a^*) values, due to the presence of hot spots. While AI thawed chicken fingers presented a significatively lower ($p < 0.05$) yellowness value (b^*) as compared to the refrigerator thawed one. Even though colour differences in raw chicken fingers are not meant to be seen by costumers, it was previously reported that an increase in yellowness values could be concurrent with lipid oxidation upon freeze-thaw cycles (Ali, Rajput, Li, Zhang &

Zhou, 2016). Hence, it is possible that shorter thawing by AI, as compared to refrigerator, could be beneficial for reducing the development of oxidation phenomena.

Table 8 Average means of colour parameters for chicken fingers thawed by air impingement, refrigerator or microwaves.

Thawing method	Thawed chicken fingers		
	Luminosity (L*)	Redness (a*)	Yellowness (b*)
Air impingement	49.8 ± 1.9[b]	1.4 ± 0.5[a]	5.0± 0.9[b]
Refrigerator	50.3 ± 1.7[b]	1.4 ± 0.6[a]	5.4 ± 1.0[a]
Microwaves	53.5 ± 5.7 [a]	0.9 ± 0.8[b]	5.4 ± 2.0[ab]

[a,b] for each property, means indicated by the same letter are not significantly different ($p > 0.05$).

After thawing, chicken fingers were breaded with a commercial breading mix and fried. Cooking loss and firmness of fried products are presented in Table 9. Cooking loss of AI thawed chicken fingers was significantly lower ($p < 0.05$) than microwave thawed ones. Moreover, cooking loss after both treatments were comparable to refrigerator thawing one. This represents a remarkable advantage for AI thawing application in food service, as a thawing process faster than refrigerator one can be performed without affecting final product yield. Cooking loss of unfrozen chicken fingers was also analysed and resulted to be comparable to microwave thawed ones (21.3 % ± 1.0). However, in this case, the losses included the portion of water loosely held by the muscle, which was lost during thawing by the other samples. No swelling or detachment of the breading was observed during frying independently on thawing method.

Firmness of fried chicken fingers was measured after cooling, thus its value is representative of the meat core, since the crust is known to soften during cooling. Even though differences associated to the thawing method were not significant (p >

0.05), the average firmness value of AI thawed chicken fingers resulted slightly lower than refrigerator thawed ones. This small difference could be caused by the observed microstructural differences (Table 7) and possible protein modifications (Fig. 24) in raw chicken fingers. In fact, it was previously reported in section 1.3, that a more intense protein modification during thawing can cause a toughening of meat upon cooking.

Table 9 Cooking loss and firmness of chicken fingers thawed by air impingement, refrigerator or microwaves and fried.

Thawing method	Cooking loss (%)	Firmness (N)
Air impingement	20.1 ± 1.4 [b]	36.1 ± 8.7[a]
Refrigerator	20.5 ± 1.7[ab]	40.7 ± 3.8[a]
Microwaves	21.3 ± 1.0[a]	37.8 ± 6.0[a]

[a,b] for each property, means indicated by the same letter are not significantly different ($p > 0.05$).

Moisture loss and fat uptake upon frying of differently thawed samples are shown in Table 10. While moisture loss values were not significatively different ($p > 0.05$), fat uptake for AI thawed chicken fingers was lower ($p < 0.05$) than those for refrigerator or microwave thawed samples. This result might suggest that, as expected (see section 3.4.2 and 1.4), the looser/modified structure of refrigerator or microwave thawed samples allowed a larger mass exchange as compared the more compact AI thawed one. Moreover, the parallel trends of moisture loss and fat uptake were in agreement with a possible correlation of these phenomena as described in section 1.4. The lower fat uptake observed for AI thawed samples, as compared to refrigerator thawed ones, could be of interest for QSR chains, due to the calorie information labels required on menus, mentioned in section 1.1. Moreover, a reduction in frying fat volume requirements could be beneficial for a reduction of outlet expenses. Thus, an estimation of these values was performed.

USDA (2019) reported that one portion of fast food chicken tenders (roughly comparable to chicken fingers) corresponds to 184 g and 499 kcal. From our tests we calculated an average difference of 1.3 g of fat for 100 fried chicken fingers between refrigerator and AI thawed chicken fingers, corresponding to 2.4 g fat reduction per portion. Since on average one gram of fat accounts for 9 kcal, the measured difference would be roughly corresponding to 21.5 kcal/portion of chicken fingers, corresponding to an estimated reduction of 4.3% total kcal/portion. Although this reduction is far from the 30% fat reduction requested for nutrition claims by Regulation (EC) No 1924/2006, it could be beneficial when used in combination with other fat uptake reducing strategies. As for the fat consumption for the food service outlet, a rough estimation can be performed considering that a chicken based QSR serves a minimum of 20,000 chicken fingers/year (internal estimation by Electrolux Professional business department). If 0.5 g less oil is absorbed by each chicken finger (41 g circa), then 10,000 grams of fat/year less are used, corresponding to less than 1% yearly fat consumption for a chicken based QSR (internal estimation by Electrolux Professional business department). This indicates that fat saving attributable to food fat uptake would be very limited.

Table 10 Moisture loss and fat uptake of chicken fingers thawed by air impingement, refrigerator or microwaves and fried.

Thawing method	Moisture loss upon frying (g/100g)	Fat uptake upon frying (g/100g dm)
Air impingement	10.7 ± 1.1^{a}	8.8 ± 0.9^{b}
Refrigerator	12.3 ± 1.2^{a}	11.1 ± 1.0^{a}
Microwaves	12.0 ± 0.8^{a}	10.4 ± 0.4^{a}

^{a,b} for each property, means indicated by the same letter are not significantly different ($p > 0.05$).

Colour parameters of chicken fingers fried after thawing by air impingement, refrigerator or microwaves were compared (Table 11). AI thawed-fried samples showed a significatively lower ($p < 0.05$) average redness value (a*) as compared to the microwave thawed one; while microwave thawed chicken fingers showed a significatively ($p < 0.05$) higher yellowness value (b*) as compared to refrigerator thawed samples. Furthermore, AI thawed-fried chicken fingers showed the highest ($p < 0.05$) luminosity value (L*). Development of colour upon frying is affected by factor as fat hydrogenation (Ngadi, Li, & Oluka, 2007), however in our case fresh fat was used for each frying test, and same frying conditions were used. Therefore, darker colour by refrigerator or microwave thawing may be indicative of a higher rate of Maillard browning reaction and caramelization (Sunisa, Worapong, Sunisa, Saowaluck, & Saowakon, 2011). Rate of non-enzymatic browning depends on food chemical composition but could be also affected by protein physical structure and availability (Carabasa & Ibarz, 2000); thus, it cannot be excluded that protein physical alterations observed after refrigerator or microwave thawing (Fig. 19, Fig. 21) may be involved in the darkening phenomena. If such hypothesis is correct, interesting findings could result from future analysis of processing contaminants, as acrylamide, associated to AI thawing-frying processes. Moreover, it is known that a reduction of moisture levels can increase the rate of Maillard reactions (Labuza & Baisier, 1992). It is then possible that, as compared to AI thawed chicken fingers, the refrigerator or microwave thawed samples gained redness due to their higher (even though not significatively different) water loss upon frying (Table 10).

Table 11 Average means of colour parameters for chicken fingers fried after thawing by refrigerator, air impingement or microwaves.

Thawing method	Fried chicken fingers		
	Luminosity (L^*)	Redness (a^*)	Yellowness (b^*)
Air impingement	53.5 ± 2.7^{a}	13.9 ± 1.5^{b}	27.6 ± 2.7^{ab}
Refrigerator	52.2 ± 2.8^{b}	14.2 ± 1.4^{ab}	26.8 ± 2.8^{b}
Microwaves	51.8 ± 3.2^{b}	14.8 ± 1.7^{a}	28.0 ± 3.2^{a}

^{a,b} for each property, means indicated by the same letter are not significantly different ($p > 0.05$).

Sensory analysis was performed on differently thawed fried chicken fingers. Results are shown in Fig. 26. No significative differences ($p > 0.05$) were perceived by untrained panellists for browning, visible greasiness, crunchiness and meat firmness of the samples depending on thawing method ($p < 0.05$). These results were in agreement with instrumental measurements of firmness (Table 8); Moreover, they demonstrate that instrumentally observed differences in luminosity (Table 10) and fat uptake (Table 9) were not significantly perceivable by final customers. Nevertheless, three panellists indicated in their optional comments that AI thawed samples were juicier than reference, while only one did so for refrigerator or microwave thawed chicken fingers.

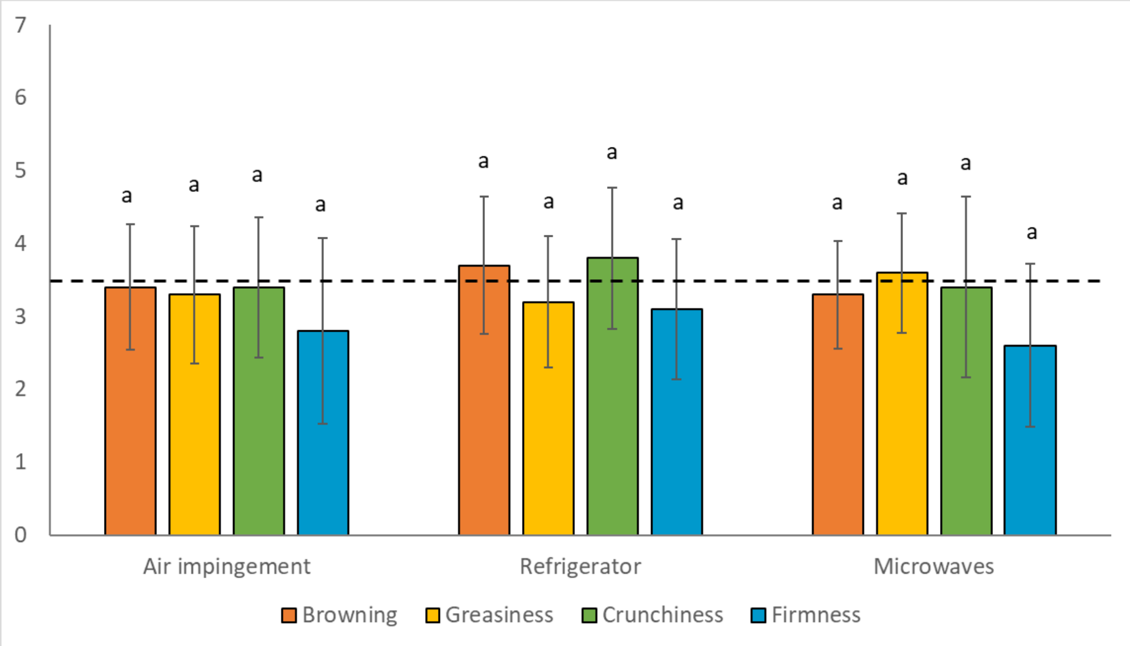


Fig. 26 Sensory scores of fried chicken fingers thawed by air impingement, refrigerator, and microwaves. Black dotted line represents the value assigned to the reference sample (refrigerator thawed). For each property, means indicated by the same letter ([a])are not significantly different ($p > 0.05$).

3.5.3 Conclusions

Structural differences observed between chicken fingers thawed by refrigerator and AI did not affect their cooking loss upon frying. In contrast, evident modifications observed on microwave thawed samples were associated with a significative reduction of cooking yield. Interestingly, a slightly lower fat uptake and higher luminosity were observed for AI thawed samples, possibly due to the structural preservation of meat. Although these changes were instrumentally measurable, sensory analysis demonstrated that consumers were not able to discriminate thawed chicken fingers based on visible greasiness and colour.

In summary, these results - in addition to those obtained so far in sections 3.3 and 3.4 - demonstrate that AI can be considered a valid alternative for chicken fingers thawing before frying.

3.6 – Efficacy of air impingement thawing on typical thawed-fried commercial food for food service.

In previous sections AI proved to reduce thawing time of chicken fingers as compared to conventional refrigerator thawing, with good or comparable results in terms of yield and food performances. However, to fully acknowledge this method as a valid alternative for QSR thawing, it is important to assess its versatility, being defined (section 1.5) as the ability to give good thawing performances on different food types. Indeed, food matrices with different composition and structure could show results not in line with those observed for chicken fingers. Moreover, since frying performances depend on mass and energy transfers, different coatings could hinder or emphasise differences in frying performances of AI thawed food. Aim of this section was therefore to evaluate the versatility of AI thawing method. To this aim, AI thawing performances of different food products were analysed in comparison with analogous samples thawed by other food service thawing methods. In order to accurately reproduce common food service practices, professional chefs from the Centre of Excellence by Electrolux Professional were interviewed to define food types, portions, thawing methods, thawing process parameters, food coating and frying conditions. Performances for all combinations of food products and thawing methods - in terms of thawing time, thawing loss, cooking loss, firmness of fried product, fat uptake and colour - were analysed and discussed.

3.6.1 Materials and methods

Selection of food products and thawing conditions

Professional chefs from the Centre of Excellence by Electrolux Professional were interviewed to define experimental conditions representative of food service practices. In particular, food types which are thawed before frying, their size and portion, common thawing methods, thawing process parameters, food coating and frying conditions were inquired.

Experimental plan

Frozen food products were thawed, coated, fried (Fig. 27) and analysed according to experimental plan in Fig. 28. Thawing time, hot spot temperature measurement, thawing loss, cooking loss, fat uptake and statistical analysis were performed according to methods described in sections 3.3, 3.4 and 3.5.

Sample preparation

Commercial French fries, coated with modified starch (*) and par-fried (Dippers, Lamb Weston Holdings Inc, Idaho, USA), squid cut in rings and tentacles (Clean Patagonian Squid, Marfrìo SA, Pontevedra, Spain) and cod fillets (s/p 80-100 g Sea Frozen BV, Urk, Holland) were purchased from a food service supplier (MARR SpA, Rimini, Italy). All samples were delivered as frozen and kept at -18 °C until use.

(*) Ingredients: potatoes 88%, coating 7% (modified starch, rice flour, salt, leavening agents E450, E500), starch, thickening agents E415, spice extracts (paprika, turmeric), dextrose, sunflower oil 5%.

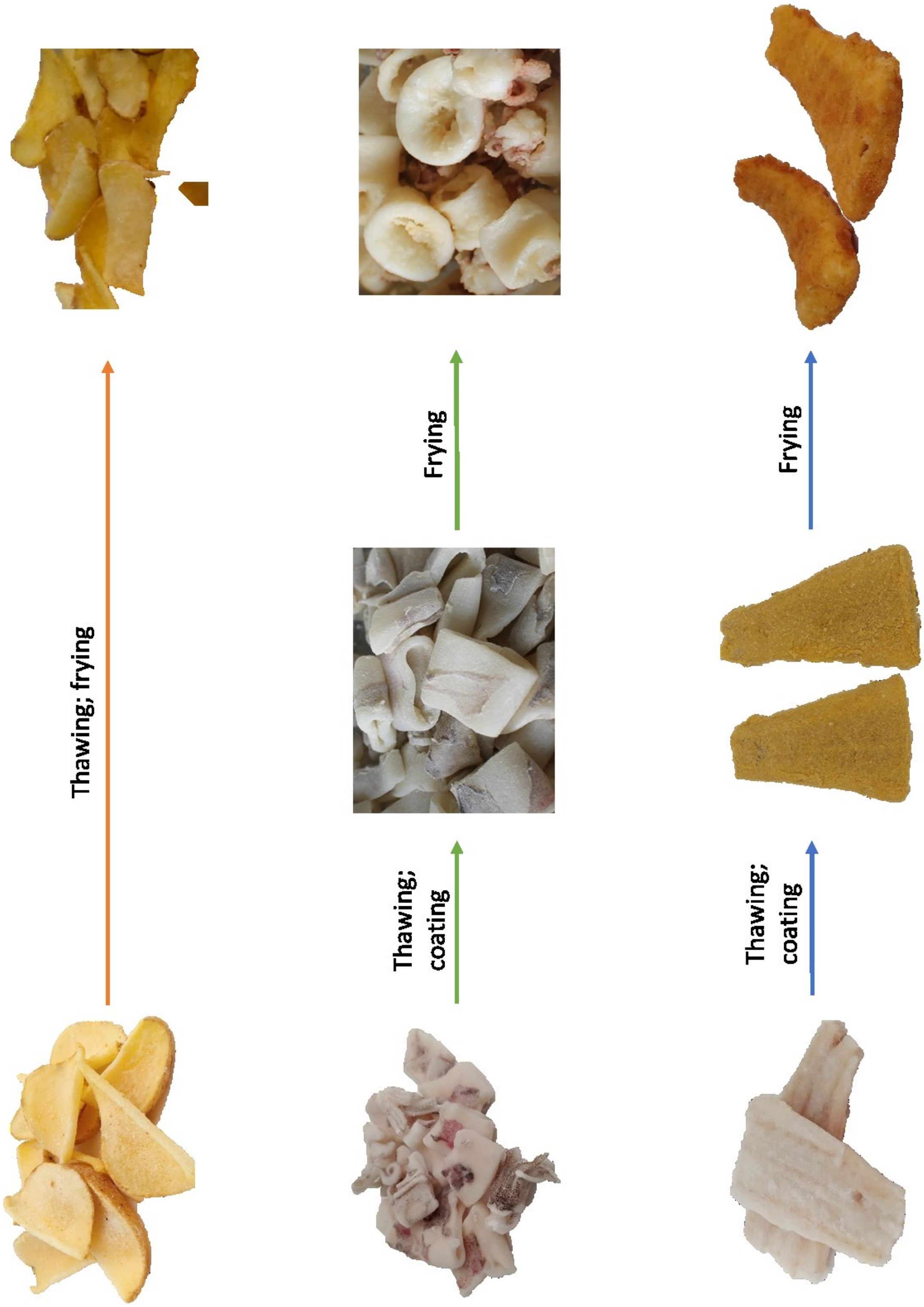


Fig. 27 Fried French fries, squid and cod fillets preparation steps.

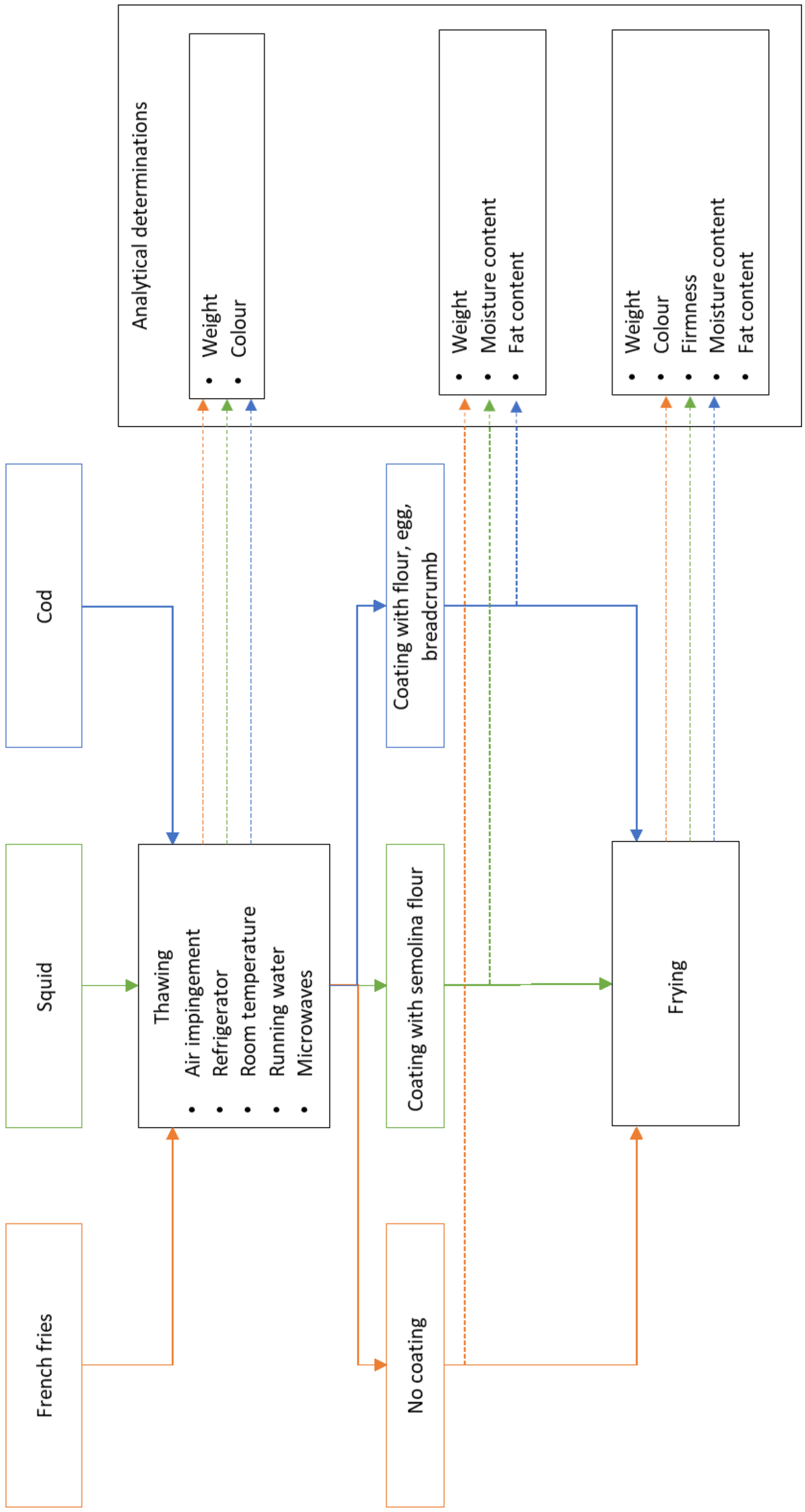


Fig. 28 Experimental plan to evaluate the effect of the thawing method on fried food.

Thawing

Aliquots of 200 g of French fries, 270 g of squid and 2 cod fillets (220-240 g) were used for the tests (scale PKS 200-3 Kern-Sohn, Belingen, Germany). Samples were thawed in perforated trays above collect trays, except for microwave thawing and AI thawing (see below). Thawing processes, were completed when whole food reached 0 °C (see *Temperature measurement* below). The following thawing methods were applied:

- Air impingement: samples were inserted in moisture impermeable polyethylene bags (20 × 30 cm; thickness 95 μm, Minipack-Torre SpA, Dalmine BG, Italy) sealed with a vacuum sealer (EVP45, Electrolux Professional SpA, Italy) and thawed in the air impingement prototype (described in section 3.1). Thawing was performed according to cycle E reported in Table 2.
- Refrigerator: trays were covered with PVC film and thawed at 4.0 ± 1.0 °C in a food service refrigerator (Electrolux Ecostore Premium, Electrolux professional SpA, Italy).
- Room temperature: trays were covered with PVC film and thawed at 25.0 ± 1.0 °C.
- Running water: trays with samples were filled with tap water (17.0 ± 1.0 °C) at a controlled flux, avoiding direct jet of water on food. Water was left overflowing during the thawing process.
- Microwaves: samples were placed on a ceramic dish and thawed in a microwave oven (Electrolux Mod. EVY7800ZOZ, Electrolux SpA, Stockholm, Sweden) at 100 W.

Temperature measurement

Frozen food products were drilled (GSR 18 V-LI Professional, Robert Bosch GmbH, Gerlinger, Germany) to the geometric core of their thickest part with a drill bit of 1.65×10^{-3} cm. T-type thermocouples (Tersid Srl, Milan, Italy) were inserted in the holes to monitor food temperature during thawing. Before starting the thawing tests, products were placed again in the freezer until monitored temperature dropped at -18 °C. For microwave thawing, the temperature of the samples was monitored at the end of the thawing process. Data were recorded using a multimeter (Data logger 34972A with multiplex 34901A, Agilent, Santa Clara, California).

Coating

Squids were coated with re-milled durum wheat semolina (Molino Spadoni SpA, Coccolia, Italy). Cods were coated with flour (Calibrata, Molino Spadoni SpA, Coccolia, Italy), manually soaked in whole eggs mix (made from fresh eggs) and covered with milled bread (sieved to remove particles above 1.75 × 10^{-3} cm) (Dolpan S.r.l, Treviso, Italy). Flour/breading excess was removed by placing samples in a sieve (1.75 × 10^{-3} cm) and shaking the products.

Frying

Each aliquot of sample (see *Thawing* section above) was fried in a tabletop fryer (Tefal F63-M1, Rumilly, France) in 2.8 L sunflower oil (DAC SpA, Flero, Italy), changed after each cooking test. Cod fillets were fried at 180°C for 3 min (flipped with a fork after 2 min), French fries at 190 °C for 2 min and squid at 190°C for 1 min. After frying, samples were drained shaking the frying basket and put on fat absorbing paper for restaurants and blotted for 3 seconds each side. Samples were then placed on griddles to cool down at room temperature for circa 45 min.

Firmness

Firmness was measured as described in section 3.4. French fries were cut perpendicular to the longer side, convex upwards; squids were cut in half in correspondence to the diameter of the ring; cod fillets were cut perpendicularly to the longest side.

Colour

L*, a*, b* colour parameters were measured as described in section 3.4. For French fries, potato peel was not measured; for squid, only rings were measured, and coloured skin parts were avoided; for cod, only the lightest of the two sides was measured.

3.6.2 Results and discussion

From professional chefs' interviews, it emerged that, among food thawed and fried in food service, the vast majority is of animal origin. Since meat was already considered in previous sections (chicken fingers), a fish (cod) and a cephalopod (squid) were chosen for the experimentation. Nonetheless, a plant-based food was also selected for a broader coverage of different food types. In particular, French fries were chosen as few operators and authors were reported to thaw them, possibly with the aim of reducing frying times (Abdul Hamid, Omar & Sanny, 2019). Moreover, commercial French fries might be blanched, coated with starch and par-fried before freezing. French fries, squid and cod were chosen also because of the different coating applied after thawing: a multilayer of flour, egg and breadcrumbs for cod; flour for squid; none for French fries. As for the thawing methods, besides refrigerator and microwave, also running water thawing was included as chefs reported that it is sometimes used for fish thawing. Room temperature thawing, even though considered an unproper thawing method, was also considered for comparison. While for other methods the thawing process parameters were defined by the chefs, for AI thawing cycle E (Table 2) was applied; it is noteworthy that this thawing cycle was not optimized for these products, contrarily to what was performed for chicken fingers.

Thawing time for each combination of product and thawing method are reported in Table 11. It should be mentioned that squid and cod units presented an external crust of ice, which likely affected the thawing processes. As observed for chicken fingers, refrigerator thawing was the slowest method. Compared to it, room temperature thawing, thanks to its higher air temperature (25°C) reduced thawing time by more than 63%, even though air was almost still. AI method beneficiated of the air speed and - compared to refrigerator method - reduced the thawing time by 83 to 90%. The fastest method was running water thawing, reducing thawing time by more than 97% for all products and at second place there was microwaves thawing, which reached at least 94% of time reduction. However, also for these food types microwaves led to an evident uneven thawing with parts of food reaching temperatures up to 65 °C for cod (54 °C for French fries and 46 °C for squid). In figure 30 it is possible to observe overheated zones of cod fillets (circled); the runway effect in this case was probably emphasized by the irregular shape and thickness of the product.

Table 11 Thawing time of French fries, squid and cod fillets thawed by different thawing methods.

Thawing method	Thawing time (h)		
	French fries	Squid	Cod
Air impingement	0.4 ±0.1	0.5 ±0.1	2.1 ±0.2
Refrigerator	4.0 ±0.2	3.5 ±0.2	12.0 ±0.3
Room temperature	1.3 ±0.2	1.3 ±0.2	2.5 ±0.3
Running water	0.1 ±0.1	0.1 ±0.1	0.2 ±0.1
Microwaves	0.2 ±0.1	0.2 ±0.1	0.3 ±0.1

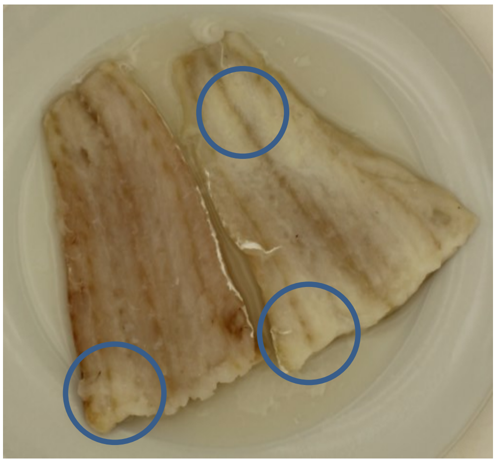


Fig. 30 Microwave thawed cod fillets. Overheated zones are highlighted by circles.

Thawing loss for all combinations of food types and thawing methods are reported in Table 12. For all food types, thawing loss for AI thawed samples was not significatively different ($p > 0.05$) from refrigerator thawed one, in agreement with results relevant to chicken fingers. However, while for squid no effect of the thawing method was observed, some significative differences in thawing loss were observed for thawed French fries and cod. In particular, average thawing loss of French fries and cod thawed by microwaves was higher than that of samples thawed by refrigeration. It is possible that the local temperature reached in cod hot spots (65 °C), which was higher than the one measured for chicken fingers (45 °C), was sufficient to cause the increase of thawing loss. In contrast, running water thawing led to negative values of thawing loss for French fries, indicating an absorption of water by potato tissues. Moreover, running water thawed cod showed significantly lower ($p < 0.05$) thawing loss as compared to refrigerator method, even if comparable to that of AI thawed samples. It is possible that running water thawing only hindered thawing losses for cod, while potato tissue, especially after the typical commercial pre-treatments (e.g. blanching or pre-frying), was more permeable to water.

Table 12: Thawing loss of French fries, squid and cod fillets thawed by different thawing methods.

Thawing method	Thawing loss (%)		
	French fries	Squid	Cod
Air impingement	0.5 ± 0.3^{ab}	24.7 ± 2.1^{a}	22.3 ± 1.6^{bc}
Refrigerator	0.0 ± 0.4^{b}	24.1 ± 2.4^{a}	23.7 ± 2.6^{ab}
Room temperature	0.1 ± 0.4^{b}	21.8 ± 1.8^{a}	24.3 ± 1.8^{ab}
Running water	-14.7 ± 1.9^{c}	21.2 ± 1.4^{a}	18.9 ± 2.6^{c}
Microwaves	0.8 ± 0.5^{a}	22.0 ± 2.1^{a}	27.1 ± 3.3^{a}

^{a,b,c} for each product, means indicated by the same letter are not significantly different ($p > 0.05$).

Colour parameters of samples thawed by different methods are reported in Table 13. In general, significative ($p < 0.05$) differences were observed depending on the thawing method. Notably, for cod, the highest luminosity, yellowness and lowest redness ($p < 0.05$) were observed after microwave thawing, as expected due of the presence of hot spots. While, unexpectedly, all AI thawed samples showed the highest redness values (a*). For French fries, which were pre-fried, redness could be partly affected by thawing method ability to maintain pre-formed pigments from Maillard reaction on food surface as previously hypothesised by Gennadios, Hanna and Ling (1997). While for raw squid, since a reduction of redness is observed as a consequence of oxidizing agents on chromatophores, it could be surmised that thawing by AI, which took place in bags instead that on trays, exposed squids to a less oxidising environment, keeping a slightly pinker coloration (Sungsri-in, 2010; Sungsri-in, Benjakul, & Kijroongrojana, 2011).

Table 13 Colour parameters of French fries, squid and cod thawed by different thawing methods.

Thawing method	Colour of thawed French fries			Colour of thawed squid			Colour of thawed cod		
	Luminosity (L*)	Redness (a*)	Yellowness (b*)	Luminosity (L*)	Redness (a*)	Yellowness (b*)	Luminosity (L*)	Redness (a*)	Yellowness (b*)
Air impingement	63.5 ± 6.2^{bc}	-3.4 ± 2.7^{a}	23.0 ± 7.5^{a}	58.0 ± 1.8^{a}	-2.1 ± 0.4^{a}	-1.4 ± 1.0^{c}	54.2 ± 1.8^{b}	-0.8 ± 0.5^{a}	1.2 ± 1.6^{d}
Refrigerator	69.3 ± 3.7^{a}	-8.3 ± 0.8^{b}	24.4 ± 5.5^{a}	56.8 ± 2.9^{b}	-5.4 ± 0.5^{e}	2.1 ± 2.7^{a}	52.7 ± 2.3^{c}	-4.0 ± 0.6^{b}	5.0 ± 2.0^{b}
Room temperature	65.6 ± 3.9^{b}	-8.3 ± 0.8^{b}	24.1 ± 4.6^{a}	55.9 ± 3.2^{b}	-4.0 ± 1.6^{b}	0.9 ± 2.4^{b}	53.3 ± 2.2^{c}	-4.2 ± 0.7^{b}	4.7 ± 1.5^{bc}
Running water	64.0 ± 3.4^{c}	-8.7 ± 0.9^{c}	22.3 ± 5.1^{a}	54.1 ± 2.7^{c}	-5.1 ± 0.4^{d}	2.5 ± 1.5^{a}	52.9 ± 3.4^{c}	-4.2 ± 0.7^{b}	4.3 ± 1.9^{c}
Microwaves	65.8 ± 4.4^{b}	-9.1 ± 1.1^{d}	23.5 ± 5.1^{a}	54.5 ± 3.7^{c}	-4.9 ± 0.7^{c}	2.6 ± 1.9^{a}	58.2 ± 6.8^{a}	-4.9 ± 1.1^{c}	6.3 ± 2.5^{a}

^{a,b,c,d} *for each column, means indicated by the same letter are not significantly different ($p > 0.05$).*

After thawing, samples were coated according to experimental plan in Fig. 28 and fried. Cooking loss upon frying (Table 14) differed noticeably between food types because of different food matrixes, pre-treatments (i.e. French fries) and coatings, which influenced mass transfers. Nonetheless, for all products no significant difference ($p > 0.05$) was observed depending on thawing method. Comparable values for AI and refrigerator thawed samples cooking loss were in agreement with the findings of section 3.5, relative to chicken fingers. However, contrarily to what observed for chicken fingers, for these three products also microwaves did not cause significative differences in cooking loss as compared to refrigerator thawing.

Table 14 Cooking loss of French fries, squid and cod fillets thawed by different thawing methods.

Thawing method	Cooking loss (%)		
	French fries	Squid	Cod
Air impingement	21.4 ± 2.0[a]	33.4 ± 2.3[a]	3.5 ± 1.3[a]
Refrigerator	19.4 ± 2.6[a]	31.3 ± 4.7[a]	3.9 ± 1.9[a]
Room temperature	21.7 ± 3.9[a]	30.2 ± 3.4[a]	3.2 ± 0.8[a]
Running water	24.4 ± 3.3[a]	28.9 ± 4.2[a]	2.7 ± 1.2[a]
Microwaves	20.6 ± 2.7[a]	26.8 ± 4.8[a]	5.7 ± 3.0[a]

[a] *for each product, means indicated by the same letter are not significantly different ($p > 0.05$).*

Firmness of fried products, representative of the mechanical properties of the inner portion of the products, is presented in Table 15. Firmness of AI and refrigerator thawed samples was comparable ($p > 0.05$) for squid and cod, in agreement with results for chicken fingers. However, a difference was observed for French fries. In fact, both refrigerator and running water thawed French fries were significantly softer ($p <0.05$) than AI and microwave thawed ones. As for running water thawing, it was hypothesized that a partial removal of the superficial starch coating or of soluble pasting agents from intracellular spaces of potato tissue could have taken place during thawing. In fact, during cooking, soluble pectines and protopectins add strength to the structure in contrast with starch gelatinization and swelling, which lower the breaking resistance by softening the tissue, increasing porosity and separating cells (Lisińska, Tajner-Czopek & Kalum, 2007; van Koerten, et al., 2015). For refrigerator thawing, it is possible that recrystallization phenomena during the longer thawing time could have affected the vegetable tissues reducing the firmness. Firmness of fried squid resulted independent ($p > 0.05$) on the applied thawing method. Finally, for cod, the only significant difference in firmness ($p < 0.05$) was observed for microwave thawed samples. This result, in disagreement with data for chicken fingers, could be imputable again to the higher temperatures reached locally during cod thawing. In fact, an increase of firmness for fish can be linked with protein denaturation (Alizadeh et al. 2007).

Table 15 Firmness of French fries, squid and cod fillets thawed by different thawing methods.

Thawing method	Firmness (N)		
	French fries	Squid	Cod
Air impingement	9.0 ± 1.9[a]	14.5 ± 3.3[a]	6.3 ± 1.8[b]
Refrigerator	7.3 ± 2.4[b]	14.1 ± 4.1[a]	6.8 ± 2.2[b]
Room temperature	8.5 ± 2.6[ab]	14.3 ±2.8[a]	7.1 ± 2.5[b]
Running water	7.0 ± 2.3[b]	14.4 ± 3.6[a]	6.8 ± 1.3[b]
Microwaves	9.7± 3.0[a]	17.0 ± 4.5[a]	11.7 ± 4.4[a]

[a,b] for each product, means indicated by the same letter are not significantly different ($p > 0.05$).

Fat uptake upon frying for all products is presented in Table 16. Again, a large effect of food type was observed. This can be attributed to different food matrixes, surface/volume ratio, commercial pre-treatments (French fries) and coating. However, no significative differences ($p > 0.05$) in relation to the thawing method were observed. This result does not agree with that observed for chicken fingers and is possibly attributable to the different matrices and coatings.

Table 16 Fat uptake upon frying for French fries, squid and cod differently thawed.

Thawing method	Fat uptake upon frying (g/100g dm)		
	French fries	Squid	Cod
Air impingement	8.2 ± 2.5[a]	25.2 ± 1.7[a]	16.8 ± 2.5[a]
Refrigerator	9.9 ± 2.2[a]	24.3 ± 0.8[a]	17.8 ± 2.4[a]
Room temperature	13.1 ± 4.1[a]	23.5 ± 1.7[a]	16.5 ± 2.7[a]
Running water	13.1 ± 3.0[a]	21.3 ± 2.7[a]	20.4 ± 6.1[a]
Microwaves	11.9 ± 2.5[a]	21.8 ± 1.8[a]	16.7 ± 2.5[a]

[a] *for each product, means indicated by the same letter are not significantly different ($p > 0.05$).*

Colour parameters of the fried samples were measured and reported in Table 17. As for thawed products, significative ($p < 0.05$) differences were observed depending on the thawing method. Remarkably, AI thawed-fried samples showed again the highest redness (a*) but also the lowest yellowness (b*) values. For fried potatoes, it was previously reported that an increase of redness (a*) and a decrease of yellowness (b*) are undesired (Krokida, Orepoulou, Maroulis, & Marinos-Kouris, 2001). Consequently, AI thawing might be considered negative for French fries' colour. In addition, observed luminosity values of AI thawed-fried products did not support the hypothesis (section 3.5) of a positive effect of this thawing method in reducing non-enzymatic browning reactions.

Table 17 Colour parameters of French fries, squid and cod fried after thawing by different methods.

Thawing method	Colour of fried French fries			Colour of fried squid			Colour of fried cod		
	Luminosity (L^*)	Redness (a^*)	Yellowness (b^*)	Luminosity (L^*)	Redness (a^*)	Yellowness (b^*)	Luminosity (L^*)	Redness (a^*)	Yellowness (b^*)
Air impingement	65.6 ± 3.8^{b}	-5.8 ± 0.8^{a}	21.0 ± 3.1^{d}	69.5 ± 2.6^{ab}	-1.9 ± 0.7^{a}	11.1 ± 1.4^{d}	56.6 ± 3.2^{c}	5.6 ± 2.4^{a}	27.4 ± 2.6^{d}
Refrigerator	69.3 ± 3.5^{a}	-9.0 ± 1.2^{c}	26.1 ± 4.9^{ab}	69.4 ± 3.3^{ab}	-6.7 ± 0.9^{cd}	17.2 ± 2.4^{ab}	58.5 ± 3.3^{b}	-1.0 ± 2.2^{d}	33.9 ± 2.2^{b}
Room temperature	64.5 ± 3.8^{ab}	-8.4 ± 1.4^{b}	26.7 ± 5.2^{a}	69.3 ± 2.5^{ab}	-6.5 ± 1.1^{bc}	16.2 ± 2.1^{c}	59.8 ± 2.7^{a}	-0.4 ± 2.1^{c}	35.1 ± 2.4^{a}
Running water	65.4 ± 4.7^{b}	-8.3 ± 1.4^{b}	24.0 ± 5.9^{c}	68.8 ± 2.2^{b}	-6.3 ± 1.1^{b}	17.8 ± 1.9^{a}	59.0 ± 4.0^{ab}	1.2 ± 3.3^{b}	30.7 ± 3.9^{c}
Microwaves	61.2 ± 3.7^{c}	-8.5 ± 1.7^{bc}	24.9 ± 5.0^{bc}	70.2 ± 2.0^{a}	-6.8 ± 0.8^{d}	16.6 ± 1.7^{bc}	58.3 ± 3.4^{b}	-0.1 ± 2.2^{c}	33.1 ± 2.7^{b}

[a,b,c,d] *for each column, means indicated by the same letter are not significantly different ($p > 0.05$).*

3.6.3 Conclusions

AI noticeably (by at least 83%) reduced thawing time for all considered food types (French fries, squid, cod) as compared to refrigerator thawing. Even though thawing time was not as short as that associated to running water or microwave thawing, it was still advantageous considering the processing implications and effects on food of these two methods respectively. Some possible limitations were observed for AI thawed French fries frying performances (firmness and colour), nonetheless, squid and cod results were in line with those associated to refrigerator method, in agreement with those previously observed for chicken fingers. These results suggest that AI is suitable for thawing animal products (meat, fish, cephalopods) independently on the coating applied before frying. Considering that the vast majority of food thawed before frying in food service is of animal origin, these results further support AI as a promising alternative for food service and QSR thawing before frying.

Chapter 4 Final remarks

In this PhD thesis, a multidisciplinary approach was used for evaluating air impingement thawing method suitability as an alternative to conventional refrigerator thawing for quick service restaurants.

This activity was carried out as part of a wider project in The Research Hub™ by Electrolux Professional aiming at the development of thawing appliances based on air impingement. In particular, this Ph.D. project fell within the company *Advanced Development* activities, which are delivered before the *Product Development* phase, when the considered technology has a low Technology Readiness Level (TRL) (Fig. 31). In the case of air impingement thawing, the technology concept had already been formulated (TRL 2) and proven in literature (TRL 3). However, data relevant to its evaluation on real food cases were very limited. Moreover, an appliance/prototype complying with food service operator needs had still to be developed. Hence, the TRL for air impingement thawing was at level 3 at the beginning of this PhD project (Fig. 31). Target of raising its level to 4-5 was reached by validating it on real cases and in a more relevant environment, being the company experimental kitchen. In particular, the study case, bags of chicken fingers, was selected to replicate a food product commonly thawed in quick service restaurants before frying.

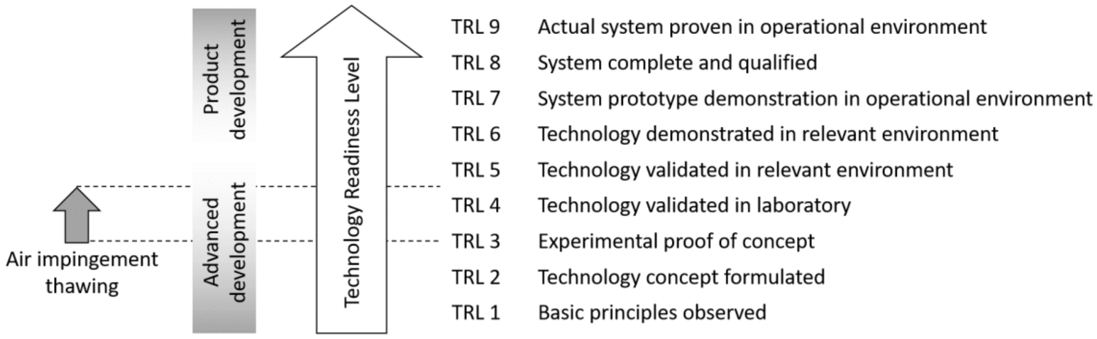


Fig. 31: Schematic representation of the Technology Readiness Level (TRL) target increase of air impingement thawing within this PhD project, related R&D department in charge for the activities and TRL levels definitions (from Héder, 2017).

To this aim, a combination of disciplines was utilised to capture the potential of air impingement thawing while reducing the related costs and the required experimental time. Air impingement thawing modelling, mechanical engineering and DOE statistical analysis were used to develop an efficient prototype, compliant with food service geometrical and cost requirements. This sub activity also contributed to define the product specifications for future versions of air impingement thawing appliances. The abovementioned air impingement thawing model was sequentially used in combination with mathematical optimization techniques to identify the most promising combinations, among hundreds, of processing parameters for thawing the selected food. The novel optimization approach resulting from this activity allowed to minimize simultaneously and efficiently thawing time, maximum local temperature and temperature unevenness in the food. After validation of the identified thawing processes in the prototype, the project continued with structural evaluation of thawed food samples and assessment of their quality upon frying. Successively, versatility of the air impingement thawing process was evaluated on other food matrices. For this target company chefs were involved in the definition of food samples and their preparation steps in line with real food service practices. For all foods considered in the work, a noticeable decrease of thawing time as well as no reduction of thawing and cooking losses were demonstrated. The acquired results showed some limitation for French fries thawing; nonetheless, very good results were observed for chicken fingers, squid and cod. To this regard, it is noteworthy that this project reported for the first time the effect of air impingement thawing on animal origin products and the performances of air impingement thawed food upon frying. A contribution was thus provided to enrich the limited literature about thawing effect on food frying performances.

Air impingement thawing was thus proved to be, with few limitations, a valid alternative to refrigerator method for quick service restaurants thawed-fried products, potentially allowing reduction of wastes and better living. In fact, the technology TRL was increased thanks to the activities described in this thesis so that The Research Hub™ by Electrolux Professional plans to continue the study for industrial feasibility of air impingement thawing. This goal was reached by considering the whole sequence of steps at the base of food production and applying modelling/optimization techniques. A similar strategy might be used to give new inputs to improve the reliability of industrial investigation on new technologies for the food sector.

Finally, this work demonstrates how a multidisciplinary approach, including food science, is vital for an economically sustainable evaluation of the industrial potential of alternative processing technologies. This is valid also for those companies that do not directly operate in the food market but provide equipment and services for operators. It is advisable that multidisciplinary approached research, which is reliable within PhD industrial projects, becomes more and more diffused.

Annexes

Annex A Sensorial evaluation sheet (Italian)

Nome:	Data:
Tipologia di campione: Bastoncini di pollo fritto	Codice del campione:

1. Hai ricevuto due campioni; un riferimento indicato con la lettera R e un campione identificato con un codice a 3 cifre
2. Osserva e assaggia il riferimento R che corrisponde al punto intermedio della scala
3. Sciacqua la bocca con acqua
4. Osserva e assaggia il campione
5. Indica la posizione del campione sulla scala

Riferimento

← - intenso ↓ + intenso →

Doratura |———————|———————|

Untuosità all'esame visivo |———————|———————|

Croccantezza della panatura |———————|———————|

Durezza della carne |———————|———————|

Commenti ____

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About the Author

Arianna Bozzato was born on 8 July 1985 in Udine (Italy). After the high school diploma (Maturità Scientifico-tecnologica) in 2004, she started studying Food Science and Technology at the University of Udine. She graduated from Control and Management of Food Quality Master course in 2011 with a thesis dealing with the effects of chemical, physical and biological treatments on the inactivation of *Listeria monocytogenes* and *Pseudomonas fluorescens* biofilms. Since January 2012, she has been working at Electrolux Professional Spa in the Research and Development department. In November 2017, she started her PhD, which ended in the present PhD thesis.