

ORIGINAL ARTICLE

Air impingement to reduce thawing time of chicken fingers for food service

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Abstract

Air impingement (AI) thawing was studied as alternative to time-consuming thawing, conventionally performed in refrigerators for food service. Chicken fingers' bags (200 g), surrounded by Tylose to simulate a food service grid load, were thawed in an AI prototype. Nine combinations of process parameters (distance food to nozzles, air speed, air temperature, number of stages, and stage durations) identified by genetic algorithm optimization were applied. The optimization aimed at minimizing thawing time, food overheating (above 0°C), and food temperature unevenness. Samples were assessed for thawing time (to 0°C), thawing loss, water-holding capacity, firmness, microstructure, and FTIR spectra. AI allowed up to 85% thawing time reduction compared to refrigerator ($4 \pm 1^\circ\text{C}$), while thawing loss, water-holding capacity, and firmness were not significantly different ($p > .05$). Histological analysis and FTIR spectra indicated AI as an interesting technology to preserve tissue structure.

Novelty impact statement

In this paper, air impingement (AI) is applied for the first time to quickly thaw chicken fingers while avoiding overheating (above 0°C) and structural modification of meat. These results support air impingement as a valid alternative to refrigeration thawing, commonly applied for food preparation in food service.

1 | INTRODUCTION

In quick service restaurants, large size packages (from 2 to 3 kg) of raw portioned frozen food (e.g., meat or fish) are commonly used. These products are often subjected to thawing to allow further preparation, as coating before frying, and ensure uniform cooking (Shrestha et al., 2009). In food service, thawing is performed by leaving the product in refrigerators/cold rooms (Ali et al., 2016) for long time (from hours to days). In refrigerators/cold rooms, heat is provided by convection/conduction through boundary layers of the medium (refrigerator air at circa 4°C) surrounding food surface and then by conduction into the food. As a result, thawing in food service

is a time- and space-consuming process. For this reason, operators are required to decide well in advance how much frozen food has to be moved from the frozen storage to the refrigerator chamber. With the aim of managing peaks in consumer number, an exceeding quantity of food is typically thawed, and food losses might be particularly high, depending on the operator planning skills. The current request of the food service operators is thus to reduce thawing time while guaranteeing food safety and quality.

A solution to increase the thawing rate is to use volumetric thawing methods (e.g., microwaves, radio frequency, etc.), which generate heat in the inner volume of the food. However, these methods currently do not match food service needs due to small

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loading capacity or high operating costs—both directly or indirectly for space requirements—and due to the possible development of side effects. One example is given by impairment of food quality and yields by runaway heating in microwaves, radio frequency, and ohmic thawing (Boonsumrej et al., 2007; James & James, 2010; Srinivasan et al., 1997; Xia et al., 2012). Another side effect is caused by the release of ozone by high-voltage electrostatic field, which may oxidize food surface affecting food flavor and color (Jia et al., 2017; Mousakhani-Ganjeh et al., 2016). Moreover, protein conformational changes and deterioration of food color and texture associated with high-pressure thawing were previously reported (Fernández-Martín et al., 2000; Jia et al., 2017; Leygonie et al., 2012).

Another solution to improve thawing rate could come by selecting a more efficient thawing medium. Given the higher heat transfer coefficient of water (around 1,000 W/m²K) as compared to that of air (about 10 W/m²K), water immersion thawing allows a noticeable reduction of thawing time (e.g., from 22 to 2 hr) (Anderson, Sun, et al., 2004; Leung et al., 2007; Oliveira et al., 2015). However, use of the water medium requires a connection to the water supply and drain systems, possibly implying a cost for the modification of the food service outlet layout. Moreover, this technique is generally associated with scarce control of thawing condition and excessive discharge of water (Leung et al., 2007). For instance, Martinelli et al. (2012) reported a consumption of 76.2 liters of drinking water for each kilogram of thawed meat. In addition, Lo et al. (2011) indicated that the cold water thawing is responsible for the 30% of the water consumption in a restaurant.

A third solution comes by an increase in air thawing efficiency. Indeed, air thawing 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 lower than those associated with volumetric methods. The required increase in air thawing efficiency can be reached by applying two different approaches: (i) an increase in thawing air temperature or (ii) an increase in the convective heat transfer coefficient by reducing the thickness of the thermal boundary layers surrounding the products surface. As regards air temperature, it is acknowledged that this operational parameter should not exceed 15°C to prevent microbial growth during thawing (Alizadeh et al., 2007; Ersoy et al., 2008). By contrast, the thickness of the boundary layers surrounding the product surface could be significantly reduced by increasing air speed and its impact angle on the product surface, as occurs upon air impingement thawing.

Air impingement (AI) is an efficient heating/cooling method, exploiting high-velocity jets of air (e.g., 10–100 m/s) impinged from nozzles on products surface (Sarkar & Singh, 2003). Many factors affect the efficiency of AI heat transfer, for example, geometric design of the appliance, shape of the nozzles, distance of food to nozzles, air turbulence, and air temperature (Zuckerman & Lior, 2006). Air impingement was patented by Smith (1975) and

lately applied for food drying and freezing. By contrast, its application as a thawing method was not studied until the early 2000s. Sarkar and Singh (2003) were the firsts to measure AI heat transfer coefficients in freeze-thaw regimes using copper and steel plates. Anderson and Singh (2006a) continued the analysis of effective heat transfer coefficients using an inverse heat transfer method on a nylon disk. Moreover, they developed a two-dimensional model for AI thawing using disks of Tylose gel, a meat analog product (Anderson & Singh, 2006b; Riedel, 1960), and used computational fluid dynamics (CFD) to simulate fluid flow and heat transfer (Anderson, Sarkar, et al., 2004). Heat transfer coefficient values were demonstrated to be much higher (30–180 W/m²K) than those associated with thawing in a refrigerator (Anderson, Sarkar, et al., 2004; Anderson & Singh, 2006a; Anderson, Sun, et al., 2004). More recently, Tiberi (2018) developed a mathematical model (combining CFD and finite difference heat conduction) of AI thawing of Tylose bricks, which was validated in an air impingement prototype designed for food service application. In particular, the effect of air temperature, air speed, and distance of food to nozzles was modeled in relation to temperature uniformity within sample, risk of overheated zones, and total thawing time. As regards AI thawing effect on real food, available data are still very scarce. Application of impingement with air at 15°C for thawing of fruit and vegetables was studied on a laboratory scale (Góral, 2008; Góral & Domin, 2005; Góral & Kluza, 2003). In these cases, thawing times resulted comparable or shorter than those associated with water thawing at the same temperature. The treatment was also reported to limit food thawing loss and provide good sensory properties. To our knowledge, no information is currently available about the impact of air impingement thawing on meat products.

Based on these considerations, the aim of this research was to evaluate the possibility of using air impingement to thaw frozen food intended for quick service restaurants. To this purpose, a poultry product, chicken fingers, was selected as a study case. This choice was based on: (i) necessity to be thawed before breading and frying; (ii) growing popularity worldwide, motivated by its cost-effective production, simple handling, and limited religious barriers as compared to other meat products (Augustyńska-Prejsnar et al., 2018; Petracci & Berri, 2017). Frozen chicken fingers were packed in polyethylene bags to simulate commercial bags used in food service. Thawing by air impingement was performed as a multistage heat transfer process by varying distance of food to nozzles, air temperature and air speed, and duration of each stage. The combinations of operational parameters to be applied during air impingement thawing were selected by the application of a multi-objective genetic algorithm (GA) optimization technique. Samples thawed according to the selected conditions were analyzed for thawing time, thawing loss, water-holding capacity, firmness, microstructure, and FTIR spectrum. Results were compared to those acquired by performing chicken fingers thawing in a conventional refrigerator.

2 | MATERIALS AND METHODS

2.1 | Frozen chicken fingers

Chicken fingers ($8 \times 3 \times 1.5$ cm) were manually cut with a sharp knife from fresh broiler breasts (from *pectoralis major*) provided by 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 at -18°C in a food service freezer (Prostore Premium, Electrolux Professional SpA, Italy). Five frozen chicken fingers were inserted in moisture impermeable polyethylene bags (20×30 cm; thickness $95 \mu\text{m}$, Minipack Torre SpA, Dalmine BG, Italy) and sealed with a vacuum sealer (EVP45, Electrolux Professional SpA, Italy). Bags were stored overnight at -18°C .

2.2 | Air impingement thawing prototype

A pilot AI thawing prototype was designed and assembled by Electrolux Professional (Figure 1). The system allows controlling air temperature, air speed, and the distance of food to nozzles inside the thawing chamber ($65 \times 53 \times 17$ cm). Closed-loop air circulation of the system was provided by a blower (centrifugal fan, backward curved type K3G250-RE07-07, Ebm Papst Srl, Como, Italy) and air temperature was controlled by a heater (two tubular resistors, with a total power of 1.5 kW, IRCA SpA, Treviso, Italy) and a chiller (power rate 398 W $0/10^{\circ}\text{C}$; R134a refrigerant; equipped with compressor EMT6170ZA CSIR 230V/50HZ power 1/3 hp by Embraco, Santa Catarina, Brazil). A plenum was used, above the thawing chamber, to slow down the air and to uniform its velocity profile among all the nozzles (staggered configuration, diameter of 1.2 cm, and a pitch of 7.2 cm between each nozzle). Exhaust outlets were present in the

sides of the thawing chamber. The exhaust flow from the thawing chamber was filtered (PolyuretanPolyester foam, 10 pores/inch, 20–30 kg/m^3 , Gomma Corvetto Srl, Monza, Italy) and then recirculated at the blower inlet. The activation of the power units of the prototype was recorded during the whole process by a logging software implemented in the machine.

2.3 | Combinations of parameters for air impingement thawing

Combinations of AI thawing process parameters (thawing cycles) were defined as described by Pippia et al. (2020). By this approach, a thermal model of AI thawing was considered as a black box problem and solved by a multiobjective genetic algorithm. The model, extensively described by Tiberi (2018), simulates the thermal evolution of a general object, in the present case the thermal properties of a meat analog (Tylose). The object was divided into thousands of sub-blocks and the physical equations were implemented using the finite difference heat conduction model, implementing the enthalpy method to take care of the phase change of the meat during the thawing process. The surface sub-blocks exchange heat with the surrounding by convection, using the air impingement heat transfer correlations available in literature (Zuckerman & Lior, 2006), and then exchange heat with the inner sub-blocks by conduction. Using this approach, a complete map of the instantaneous temperatures is obtained at every location of the object. Input process parameter intervals were 5.5–10.7 cm distance of food to nozzles, 13.4–30.0 m/s air speed, and 4– 15°C air temperature. Function *gamultiobj*, already implemented in MATLAB 2017b (Copyright 2007–2017 MathWorks Inc., Natick, Massachusetts), was used to run a genetic algorithm for multiobjective optimization. The parameters of the *gamultiobj*

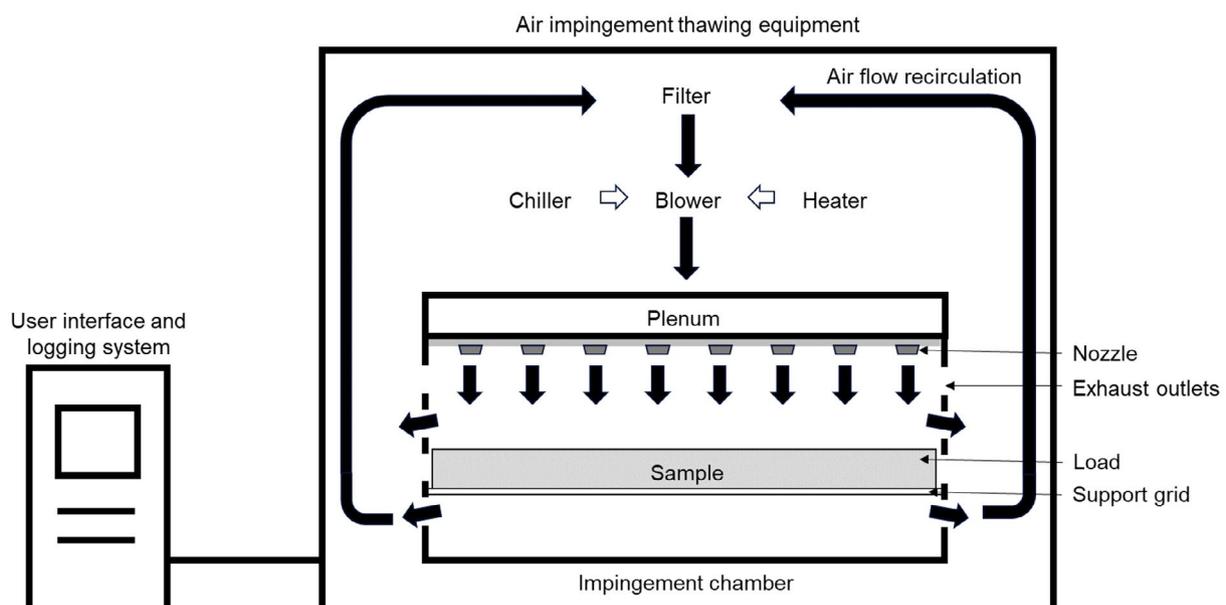


FIGURE 1 Schematic representation of the air impingement equipment

function were set up according to the process described by Pippia et al. (2020). The three objectives of the optimization problem were (i) minimization of thawing time (total time required to reach target food internal temperature of 0°C), (ii) minimization of temperature during thawing, (iii) maximization of food temperature uniformity. Among AI thawing cycles spanning the trade-off between the three objectives simultaneously, nine optimal thawing cycles were identified and reported in Table 1.

2.4 | Air impingement thawing

A chicken fingers bag was placed in the center of standard food service grid (GN 2/1 53 × 65 cm) and surrounded by 14 frozen Tylose bricks (500 g, 20 × 10 × 2 cm), to simulate a complete load of a grid during a thawing cycle. The grid was placed inside the thawing chamber (65 × 53 × 17 cm) of the pilot AI thawing equipment. Thawing process parameters were set according to thawing cycles in Table 1.

2.5 | Refrigerator thawing

The grid loaded with frozen chicken fingers was placed inside a food service refrigerator (Prostore Premium, Electrolux Professional SpA, Italy) at 4 ± 1°C.

2.6 | Temperature and thawing rate

Temperature was monitored by two thermocouples (T type, Tersid Srl, Milan, Italy) inserted in the central portion of each chicken finger or Tylose brick. Data were recorded using a multimeter (Data logger 34972A with multiplex 34901A, Agilent, Santa Clara, California). Sample temperature was defined as the highest temperature reached

by the thermocouples inserted in the central part of chicken fingers during the thawing tests. Thawing rate was calculated according to the time taken by the chicken fingers to cross the temperature zone of maximum phase transition. According to the literature, the latter occurs between 0 and -5°C (Farid, 2002; Kono et al., 2017). Thawing time was thus taken as the time until the temperature of all measured points of chicken fingers (initially at -18°C) reached 0°C.

2.7 | Thawing loss

Thawing loss was determined by weighting (scale PKS 200-3 Kern Sohn, Belingen, Germany) samples after freezing and after thawing, according to Equation (1). Thawed chicken fingers were weighted after removal from their bags and gentle blotting with cellulose paper, in order to take into account all the drips. For each treatment, at least 10 measures were performed.

$$\text{Thawing loss (\%)} = \frac{\text{Weight after freezing} - \text{Weight after thawing}}{\text{Weight after freezing}} \times 100\% \quad (1)$$

2.8 | Water-holding capacity

Water-holding capacity (WHC) of chicken fingers was determined by the filter paper press method (Grau & Hamm, 1953). Samples of 0.3 g (cubes with edges of circa 0.6 cm) were manually cut with a sharp knife from the chicken finger internal portion, always from the same position, placed onto a 7 × 7-cm² filter paper (Whatman No. 1/2) and pressed between two plexiglass plates for 5 min 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). For each treatment, at least 15 measures were performed.

TABLE 1 Thawing cycles optimized for chicken fingers (target 0°C), comprising up to three stages, to be set in the air impingement prototype

Thawing cycle	Distance food to 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	NR	NR	NR	NR
B	5.5	23.1	15	68	10	22	NR	NR
C	10.7	13.4	4	279	NR	NR	NR	NR
D	5.5	14.3	7	14	4	222	NR	NR
E	8.1	14.5	8	23	5	190	NR	NR
F	10.7	24.9	13	46	10	49	9	22
G	5.5	24.3	12	50	8	68	NR	NR
H	10.7	23.1	8	150	NR	NR	NR	NR
I	8.1	29.0	11	44	8	82	NR	NR

Note: Combinations of distance from food to nozzles, air speed, stage air temperature, and stage duration are reported.

Abbreviation: NR, stage not required to reach the target.

2.9 | Firmness

Firmness of fresh and thawed chicken fingers was measured using a Warner Bratzler (V notch) blade attached to an Instron 4,301 (Instron Ltd., High Wycombe, UK). Samples were cut parallel to muscle fibers, always in the same position for a minimum of eight measurements. The instrumental settings and operations were accomplished using the software Automated Materials Testing System (version 5, series IX, Instron Ltd., High Wycombe, UK). Test speed was 100 mm/min. Firmness was defined as the shear force (N) required to cut the chicken finger.

2.10 | Histological analysis

Internal portions of fresh, frozen, and thawed chicken fingers (cubes with edges of circa 1 cm) were cut with a microtome blade, always from the same position, and 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 embedded in paraffin (ParaplastPlus, Diapath, Martinego, Italy). Sections were cut with a programmable microtome (RM2135, Leica, Wetzlar, Germany), dewaxed and stained with Mayer's hematoxylin and eosin (Sigma Aldrich, St. Louis, MO, USA). Samples were examined using an optical microscope (DMRB, Leitz, Stuttgart, Germany), and for each sample, at least three 10× images were acquired and analyzed 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 (Equation 2):

$$\text{Intercellular area (\%)} = \frac{\text{Area of ROI}}{\text{Area of micrograph}} \times 100 \quad (2)$$

2.11 | Sample preparation, FTIR spectroscopy, and spectral processing

Thawed samples were inserted in 50-ml polypropylene centrifuge tubes and centrifuged at 15,000×g for 15 min at 4°C, as described by Grunert et al. (2016). A volume of 20 µl of the supernatant was spotted on the ATR (Attenuated Total Reflection) crystal of an FTIR spectrometer (Alpha P, Bruker, Massachusetts, USA). Spectral acquisition was performed in transmission mode in the spectral range of 4000–400 cm⁻¹. Spectral evaluation and processing was performed with OPUS 6.5 software (Bruker, Billerica USA). Averages of at least three spectra for each treatment and their second derivative (9-point Savitzky Golay filter) were normalized and compared.

2.12 | Statistical analysis

Results are presented as mean value ± standard deviation. Comparison of mean values 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 or *F*-test were applied. Depending on the result, 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 $p < .05$. Correlation analysis was performed using Excel 365 (Microsoft Corporation, Redmond, Washington).

3 | RESULTS AND DISCUSSION

3.1 | Selection and validation of AI thawing cycles

In order to speed up the experimental study and reduce its costs, multiobjective optimization methodology was used to select the most promising AI thawing cycles for chicken fingers among all possible combinations. Multiobjective problems, as a rule, present a possibly uncountable set of solutions and this set, that is, a trade-off between the chosen fitness functions, is called Pareto front. In our case, nine combinations of process parameters were selected from the obtained Pareto front and reported in Table 1. In particular, cycles A and B were chosen to minimize the total thawing time; cycles C, D, and E were selected to minimize temperature and maximize its uniformity; cycles F, G, H, and I were finally taken in the intermediate zones of the Pareto front. Each thawing cycle was composed by up to three stages (Table 1). When possible, cycles with different number of stages but aiming at the same object 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. In most cases, only one (cycles A, C, H) or two (cycles B, D, G, E, I) stages were used to reach the target food temperature (0°C). Cycle F was actually the only one requiring three different stages for sample thawing.

Validation of the applied thermal model was performed comparing experimental and predicted values of thawing time and sample temperature during thawing of chicken fingers.

Table 2 compares experimental values of thawing time for the chicken fingers thawed applying Table 1 cycles with those predicted based on model estimation. Correlation analysis was conducted to examine the relationship between experimental and predicted thawing time. A high correlation ($r = 0.91$, $p < .01$) was observed, supporting the thermal model used in the optimization methodology. Additionally, Table 2 juxtaposes predicted temperature with the experimental sample temperature of chicken fingers during thawing. The latter was comparable or lower than the predicted value during all AI cycles. Observed differences can be attributed to intrinsic variability of both food matrix and positioning of temperature sensors within the sample. Despite these results were relevant to chicken fingers placed in the center of the grid, the model was intended to predict sample temperature even in other positions. To this regard, it is noteworthy that the maximum difference between temperature recorded in chicken fingers and that measured in Tylose bricks surrounding them was lower than 5°C even during the less uniform cycles (cycles F and G).

Thawing cycle	Thawing time (min)		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

Note: Control data, relevant to chicken fingers thawed in a refrigerator at 4.0 ± 1.0°C, are also shown. Abbreviation: ND, not determined.

Table 2 also compares thawing time and chicken finger temperature upon thawing using the AI equipment and conventional refrigerator. 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 resulted equal to circa 262 min, corresponding to a 56% reduction as compared to 600 min required for thawing in refrigerator. As expected, even larger reductions of the thawing time were observed on further increase in air speed and temperature. For instance, a time reduction of 85% was observed when thawing was performed at 15°C and 30.0 m/s.

3.2 | Performance analysis of selected AI thawing cycles

Chicken fingers were thawed by applying the previously defined AI cycles (Table 1) and analyzed for thawing loss (Table 3). This parameter was selected being directly related to the final yield of thawing, which is one of the most important quality indicators for meat subjected to frozen storage. Thawing rate was also calculated as an index of heat transfer efficacy. Analogous data relevant to chicken fingers thawed in the refrigerator at 4°C are also shown in Table 3 for comparison.

Independently on the applied AI cycle, thawing loss resulted always comparable ($p > .05$) with that observed for refrigerator thawing. Moreover, no significant relation was observed between thawing loss and thawing rate by correlation analysis ($p > .05$). This can be regarded as a favorable result for food service application of AI. Indeed, meat thawing might be performed much faster without affecting the overall process yield, and thus the product economic value (Bedane et al., 2018; James & James, 2010). The lack of a linear relation between thawing loss and rate could be attributed to the counterbalancing effects of thawing rate on the maintenance of the original tissue structure. Low thawing rates may actually result in structural damage through local water recrystallization and protein denaturation, leading to higher exudate. However, high thawing

TABLE 2 Experimental and predicted values of thawing time and sample temperature of chicken fingers submitted to air impingement thawing according to different cycles

rates could hinder extracellular water reabsorption, which is known to be a slow process (Farak et al., 2009).

To further study the effect of AI thawing on meat structure, samples were analyzed for WHC, which is the ability of the tissue to retain original moisture. WHC of meat tissues was reported to be affected by freezing and thawing processes, due to proteins' modifications as the denaturation of myosin, cross-linking and aggregation of myofibrillar proteins, and formation of disulfide bonds (Li et al., 2014). Furthermore, damage of muscle tissue might form wider gaps between muscle fibers, acting as water channels and, if damage involves cell walls, intracellular components are released (Leygonie et al., 2012). In our case, WHC values (Table 3) for AI thawed samples were comparable to those of the refrigerated control ($p > .05$), in line with thawing loss results, further suggesting that thawed meat structure was not impaired by AI application.

TABLE 3 Thawing loss, thawing rate, and water-holding capacity of chicken fingers thawed using different cycles of air impingement

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}

Note: Control data, relevant to chicken fingers thawed in a refrigerator at 4.0 ± 1.0°C, are also shown. Means indicated by different letters in each column are significantly different ($p < .05$).

3.3 | Effect of AI thawing cycles on meat structure

To deeper analyze the effect of AI thawing on meat structural properties, the attention was focused on three selected thawing cycles. In particular, cycle A was chosen for being the fastest (85 min); cycle E was selected since it led to the lowest sample temperature (0.2°C); cycle H was identified among the cycles aiming to cover the intermediate zones of the Pareto front. The samples thawed by cycles A, E, and H were analyzed for firmness, microstructure by histological analysis, and FTIR spectra. Results were compared to those relevant to fresh, frozen, and refrigerator thawed samples. Table 4 shows no significant differences ($p > .05$) between firmness of fresh and thawed meat, independently on the applied thawing methodology.

TABLE 4 Firmness and intercellular area of fresh, frozen, and differently thawed chicken fingers

Sample	Firmness (N)	Intercellular area (%)
Fresh	21.3 ± 2.9 ^a	11.9 ± 0.5 ^b
Frozen	ND	39.7 ± 4.5 ^a
Refrigerator thawed	23.4 ± 2.1 ^a	27.2 ± 6.8 ^a
Cycle A thawed	21.6 ± 1.8 ^a	35.4 ± 4.7 ^a
Cycle E thawed	21.0 ± 1.8 ^a	14.9 ± 0.3 ^b
Cycle H thawed	21.8 ± 1.7 ^a	23.1 ± 1.0 ^a

Note: Means indicated by different letters in each column are significantly different ($p < .05$).

Abbreviation: ND, not determined.

Despite the similar firmness, interesting differences were observed in meat structure (Figure 2). As expected, fresh chicken fingers showed closely compacted and well-organized muscle fibers; extremely fine cracks in fibers are imputable to artifacts (Ishiguro & Horimizu, 2008). By contrast, frozen meat clearly showed the formation of big ice crystals and the occurrence of tissue damage as indicated by the deformation of cell shape. Upon thawing, ice crystals disappeared, and muscle fibers tended to recover their original volume because of the inflow of water. Gaps were still visible between fibers, reasonably due to separation of connective tissues from the muscle fibers upon formation of extracellular ice crystals. In accordance with observations by Ishiguro and Horimizu (2008), fine cracks observed in the fibers of thawed samples might also be attributable to intracellular freezing damage. In particular, they may be attributable to the above-mentioned modifications occurring to proteins upon thawing. As compared to fresh tissues, refrigerator, cycle A and H thawed samples showed a looser tissue structure, affected by the freezing–thawing process. Contrarily, cycle E thawed sample was more similar to the fresh sample and presented small gaps between fibers and a low number of visibly damaged cells. In order to confirm these observations, image analysis was performed to calculate intercellular areas in the micrographs (Table 4). Data were in line with visual observation. Intercellular area of thawing cycle E was comparable ($p > .05$) to that of fresh chicken fingers. By contrast, other thawed samples were significantly different from fresh tissue, showing a higher intercellular area indicative of higher structural modifications and comparable ($p < .05$) to that of the frozen sample. These results suggest the critical role of sample temperature minimization,

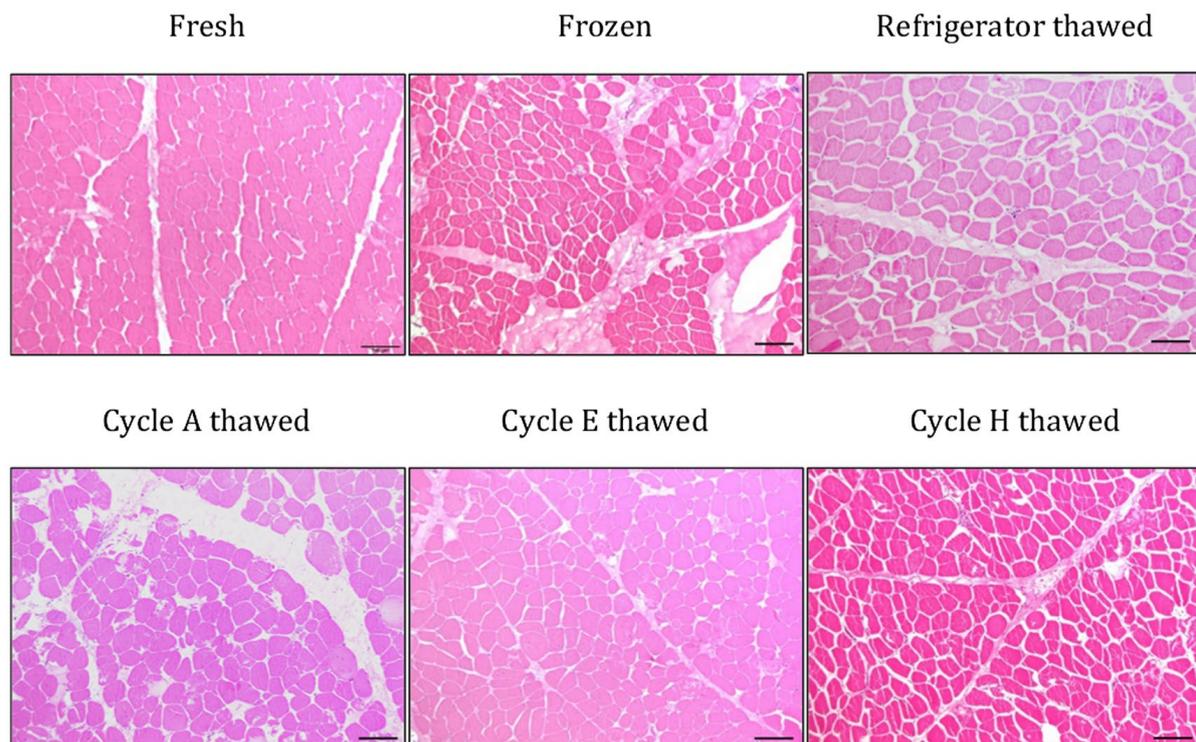


FIGURE 2 Micrographs (black scale bar equal to 100 μm) of fresh, frozen, and differently thawed chicken fingers

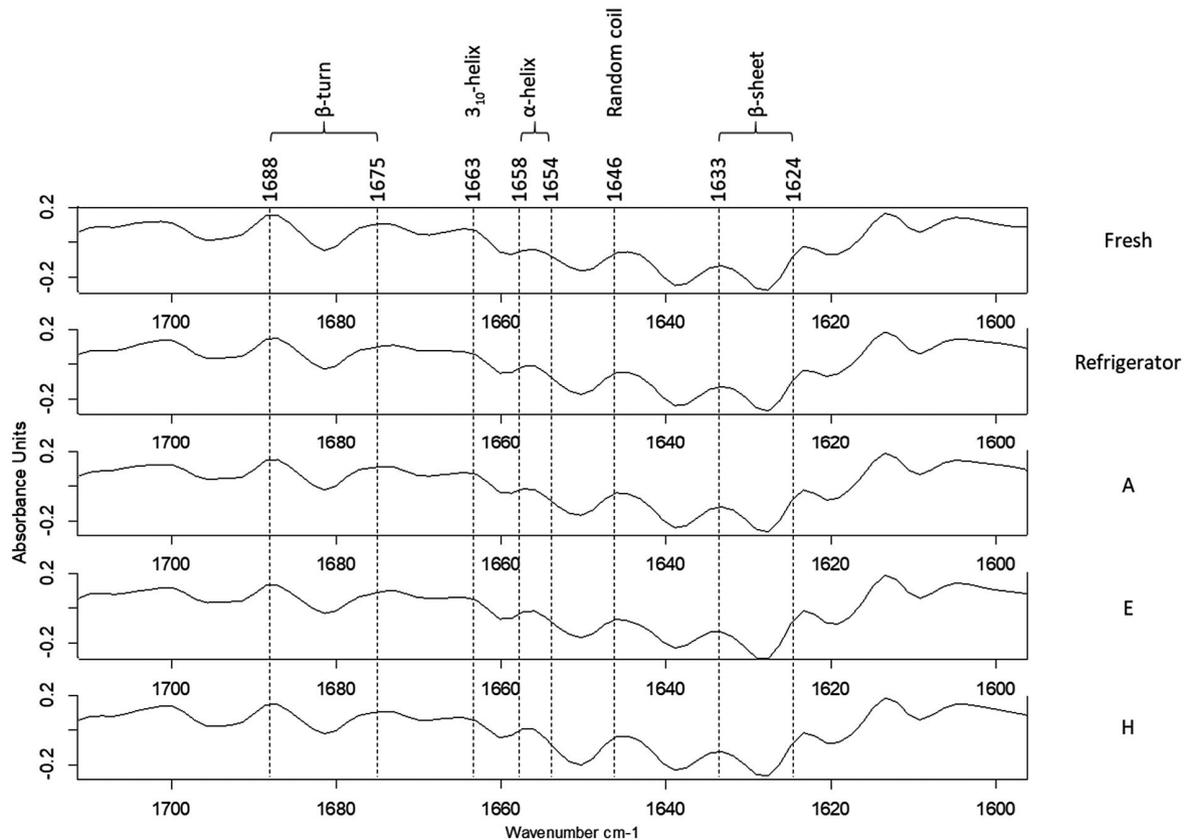


FIGURE 3 FTIR spectra second derivative of the Amide I band of chicken fingers: fresh unfrozen, refrigerator thawed, and AI thawed by cycles A, E, H

as occurs upon cycle E, in maintaining the original structural properties of meat. In other words, the possibility to decrease thawing time should be not accomplished to the detriment of sample temperature. To enlighten the effects of the different AI thawing treatments on protein structure, FTIR spectral evaluation of fresh and thawed chicken finger was performed. All spectra showed typical bands associated with amide I and II between $1,500$ and $1,700$ cm^{-1} and to alcoholic hydroxyl group around $3,300$ cm^{-1} (data not shown). The analysis of the II derivative of FTIR spectra in the Amide I range (1600 – 1700 cm^{-1}) (Figure 3) showed the typical bands associated with β sheet at 1624 and 1633 cm^{-1} , random coil at 1646 cm^{-1} , α helix between 1654 and 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). As compared to the unfrozen sample, the spectra of thawed samples showed some slight changes between β turn and 3_{10} helices band. These findings may be indicative for changes in the protein secondary structure upon freezing and thawing 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, with minor differences in other

bands. This result further supports a possible role in meat structure preservation by sample temperature minimization.

4 | CONCLUSIONS

This paper provides a first attempt to exploit air impingement (AI) for food service thawing of chicken fingers. The results show that AI thawing substantially reduces thawing time (up to 85%) compared to conventional refrigerated method. This increase of thawing rate seems not to affect negatively meat thawing loss and WHC. Moreover, a better maintenance of meat tissue organization and protein structure was observed when minimizing chicken fingers temperature during thawing. Despite these encouraging results, AI thawing is still moving its early steps and more information is needed to demonstrate its applicability in food service environment. On the one side, the acquired results, relevant to chicken fingers thawing, should be further supported by data on other food matrices as well as by information about the performance of AI thawed food upon further processing (e.g., frying, grilling, baking). On the other side, the impact of this technology on the cost and energy consumption of thawing appliances should be assessed. Finally, the compatibility of this technology within the existing food service areas and

the necessity of adapting food service operators' working routines should be carefully considered.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported

AUTHOR CONTRIBUTIONS

Arianna Bozzato: Conceptualization; Formal analysis; Methodology; Visualization; Writing-original draft. **Eleonora Pippia:** Methodology; Software; Writing-original draft. **Emidio Tiberi:** Writing-review & editing.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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