Comparison of Thawing Performance of Cycled and Inverter Microwave Heating

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Abstract. The computerized simulation of the electromagnetism and thermal defrosting were developed and validated to compare and understand the behavior of two heating processes (inverter and cyclic). Food exposure was simulated in a microwave oven cavity (2.45 GHz) using a computational model. The simulated rotational model of mashed potatoes was developed using a coding in COMSOL-MATLAB. The hot and cold spot patterns of the simulated temperature profile matched with the real ones. The heating of the mashed potatoes was not uniform in the product and the highest temperatures were observed at the edges (~ 90-95 °C). The center of the product reached temperatures of 20 °C. To compare traditional heating process, the cycling and the newest inverter, considered the shape and size of containers with mashed potatoes. The initial product temperature was -10 °C and thawed by microwave exposure for 6 minutes. The heating of the inverter did not produce differences in the absorption temperature of the mashed potatoes. The shapes and size of food are factors that affect the uniformity of heating. The small trays allowed the mash to reach an average temperature of 32 °C at 6 minutes of exposure. The round (small) and rectangular (large) vessel, allowed to reach an average temperature of 20 and 16 °C, respectively. Both types of heating presented a similar thermal non-uniformity, for the heating of mashed potatoes.

Keywords: Absorbed power, electromagnetic waves, mashed potatoes, non-uniform, simulation modeling.

Resumen. La simulación computarizada de electromagnetismo y la descongelación térmica se desarrollaron y validaron para comprender y comparar el comportamiento de dos procesos de calentamiento (inversor y cíclico). Se simuló la exposición de los alimentos en una cavidad de horno domestico a microondas (2.45 GHz) mediante un modelo computacional. El modelo rotacional simulado de puré de papas se desarrolló utilizando una codificación en COMSOL-MATLAB. Los patrones de puntos fríos y calientes del perfil de temperatura simulado coincidieron con los reales. El calentamiento del puré de papas no fue uniforme en el producto y las temperaturas más altas se observaron en los bordes (90-95 °C). El centro del producto alcanzó temperaturas de 20 °C. Para comparar el proceso tradicional de calentamiento, el cíclico y el más nuevo inversor, se consideró la forma y tamaño de los recipientes del puré de papas. La temperatura inicial del producto fue de -10 °C y se descongeló por exposición a microondas durante 6 minutos. El calentamiento del inversor no produjo diferencias en la temperatura de absorción del puré de papas. Las formas y el tamaño de los alimentos son factores que afectan la uniformidad del calentamiento. Las bandejas pequeñas permitieron que el puré alcanzara una temperatura promedio de 32 °C a los 6 minutos de exposición. el recipiente redondo (pequeño) y rectangular (grande), permitieron alcanzar una temperatura promedio de 20 y 16 °C, respectivamente. Ambos tipos de calentamiento no presentaron una uniformidad térmica similar, para el calentamiento de pure de papas**.**

Palabras clave: Desuniforme, modelo de simulación, ondas electromagnéticas, poder absorbido, puré de papas.

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1. INTRODUCTION

Microwave heating is a multiphysics phenomenon that involves electromagnetic waves and heat transfer. The heat is generated by the ability of the material to absorb microwave energy and convert it into heat (Chanrasekaran *et al.* 2013). For this reason, the design and technology of the microwave oven has been improved during the last years. Many applications have been found in food processing, such as tempering, cooking or thawing, due to its ability to produce faster heating and reduce energy consumption (Chanrasekaran *et al.* 2013).

The microwaves are electromagnetic waves which their frequencies (wavelengths) are in the range from 300 MHz (λ = 1 m) up to 300 GHz (λ =1 mm). Following international conventions, microwave ovens at home or in restaurants operate at frequencies of about 2.45 GHz, i.e. λ = 12.23 cm (Vollmer 2004.) In a microwave oven, the magnetron is used to produce the high frequency required for cooking. The magnetron is a metallic cavity with a filament that is heated to red hot and emits electrons, which combined with a powerful magnet, make electrons spin, thus generating waves (Benford *et al.* 2007). These waves are directed to the interior of the microwave cavity, bouncing against the metal walls until colliding with the food, which absorbs them, reason why a fan is used.

Traditional microwave ovens use cycled power to control the power level, where the magnetron delivers 100% of the power for a period of time and then followed by a period of time with no power. Inverter heating is a relatively new model of heating, which employs a constant lower power level with the magnetron always on (Chandrasekaran *et al.* 2013). This new approach was purposely developed to improve the heating uniformity and efficiency, as reported from Panasonic (Panasonic Services Company 2009).

The intensity of the microwaves inside the space of the device is not uniform, there are specific points where due to the bounce of the waves, it does not reach or penetrate. For this reason, the microwaves are equipped with a turntable inside. The turntable, as one of the most intuitive and common methods for increasing temperature uniformity, is used as a tray to carry and rotate the heated material in microwave ovens, to improve the temperature uniformity of microwave heating (Ye J *et al.* 2017).

Nowadays, computer simulation models are useful tools to understand and improve the designs of microwave heating systems. The commercial software COMSOL Multiphysics® 5.4 (COMSOL Inc., Boston, MA) is a software based on finite element methods that can be used to develop multiphysics models to simulate the microwave heating process. In order to develop a new model and use it for evaluation, or in this case comparison, it has to be validated experimentally with real samples. The microwave oven has different systems for heating the product, where the magnetron and its power are important. Theoretically, cycled heating and inverter heating should deliver similar time-average power in the time scale of one cycle (Chen *et al.* 2016). Prior results showed that there was no significant difference between the two heating approaches on thawing performance, in contrast with the claim of the inverter technology creator, Panasonic (Chen *et al.* 2016). Based on the results from previous researches (Chen *et al.* 2015, Morton and Hearle 2008, Pitchai *et al.* 2014, Watanabe *et al.* 2010, Rakesh *et al.* 2009), multiphysics models were developed in this study to evaluate and to compare the thawing performance using two different heating processes. For the present study, the following objectives were determined:

- Develop a simulation model heating process using COMSOL Multiphysics® 5.4 software.

- Validate a heat transfer model with experimental test based on temperature and heating patterns.

- Compare the thawing performances between cycled and inverter oven for different size and shape trays with frozen mashed potatoes.

2. MATERIALS AND METHODS

Study location.
The study was conducted at the University of Tennessee, located in the city of Knoxville, Tennessee, United States. All material preparation and the simulation model were performed in the Food Engineering Laboratory of Food Science within the University.

Simulation model development.
The computer simulation was developed using COMSOL Multiphysics® 5.4, this is a modeling and analysis tool for virtual prototyping of physical phenomena; in this study was electromagnetic and heat transfer.

Geometric model. The geometric model of the Inverter Microwave oven was developed based on Inverter Panasonic Microwave NN-SN766S. Using measuring tools (caliper and measuring tape) the dimensions of the microwave oven were taken and inserted in the COMSOL Multiphysics® 5.4 (COMSOL Inc., Boston, MA) to develop the geometry model. The same process was used for the different tray's sizes and shapes.

Governing equations. The electric field to calculate the volumetric heat source term, and conduction equations were solved by the Maxwell´s equations [1 and 2]. The mass conservation, phase change of evaporation and energy conservations equations were recollected from Chen *et al.* (2014).

Electromagnetics. The combined Maxwell´s equation was used to calculate the electromagnetic field:

$$\nabla \times {\mu_r}^{-1}\left(\nabla \times \vec{E}\right) - \left(\frac{2\times\pi\times f}{c}\right)^2 \left(\varepsilon^{\prime} - i \times \varepsilon^{\prime\prime}\right) \times \vec{E} = 0 \qquad [1]$$

∇= Vector differential operator
f = frequency (Hz)
c = speed of light (3.0 × 108 m/s)
$\vec{E}$= estimated peak electric field strength (V/m)
$\varepsilon^{\prime}$=dielectric constant
$\varepsilon^{\prime\prime}$= dielectric loss factor
μ_r^{-1}=electromagnetic permeability of the material

There was an interaction between the dielectric material (mashed potatoes) and the microwaves generating heat in the computational domain obtained from Chen *et al.* (2014). The heat source term Q_m is the internal heating from the dielectric properties from microwave irradiation:

$$Q_m = Q_{ml} + Q_{rh} \quad [2]$$

Q_{ml} = magnetic loss
Q_{rh} = resistive loss

Uniformity. To compare the heating uniformity between the two methods, the standard deviation [3], and coefficient of variance [4] were used. The standard deviation (σ) were defined by:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T(t,\overrightarrow{qi}) - \overline{T}(t))^2} \quad [3]$$

N=number of points
$\overline{T}$= average temperature (°C)
t= time (s)
$\overrightarrow{qi}$= mesh node points in mashed potatoes

The standard deviation is a measure of the non-uniformity while the coefficient of variance (COV) normalizes the standard deviation by the average temperature and was shown to be a more effective measure of nonuniformity (Geedipalli *et al*. 2007). A smaller COV represents greater temperature uniformity.

$$COV = \frac{\sigma}{\overline{T}(t)} \quad [4]$$

Mesh. For this simulation there were two mesh, one for the food (mashed potatoes) and another for the rest of the domains (microwave cavity). The figures used were tetrahedral elements and triangles elements.

The dielectric properties. The dielectric properties of the mashed potatoes were obtained from Chen *et al.* (2013). The dielectric properties were measured with an open-ended coaxial probe at 5 MHz intervals in the frequency range of 300 to 3000 MHz from -20 °C to 100 °C. Before use, the probe was calibrated with air, and deionized water (Wang *et al.* 2009).

Experimental validation.

Two replicates of mashed potatoes were heated in the microwave oven and the data obtained was compared with the simulated data to validate the accuracy of the model.

Preparation of samples. The sample consisted of a block of mashed potatoes in a plastic container. The mashed potatoes were made of 15.42% mashed potato flakes, 20.47% whole milk, 59.47% deionized water and butter 4.64%. The water and milk were heated in a beaker at 50 °C and mixed with a magnetic stirrer. The butter was incorporated to the hot solution in small slices, following Chen *et al.* (2013) research. Once all the butter was melted, the solution was added to the mashed potato flakes. All the ingredients were mixed in KitchenAid mixer for 7 minutes and were placed on the different trays for further measurement.

Methodology for experimental validation. The developed model was validated using the Inverter Panasonic Microwave NN-SN766S in a stationary position and the mashed potatoes for 1 minute of heating to make sure of where the heating patterns were, the microwave was used without the turn table in the experiment and in the simulation. The two small rectangle trays of mashed potatoes used as samples, were heated for 1 min with full power in the real microwave oven. After heating, the surface temperature distribution of the potato was captured by a Compact Thermal Imaging System, FLIR C2 (FLIR C2, Systems, Inc., Portland, USA). The simulated temperature distribution was being compared with these two experimental thermal images for validating the accuracy of the model. The minimum error accepted of difference between both was 5%.

The dimensions of the trays were measured from the real ones, validated and the volumes were compared. For the calculation of the volumes, the trays were filled with water and were weighted on the balance METTLER TOLEDO (TLE, METTLER TOLEDO, USA).

Comparison simulation model.

Numerical implementation. MATLAB® R2018 (The MathWorks, Inc., U.S.) was interfaced with COMSOL Multiphysics® 5.4 (COMSOL Inc., Boston, MA) software to simulate microwave heating of rotating food on the turntable and exporting the temperatures per location (figure 1). One complete rotation of the tray lasted 10 seconds, and at the end of the 10 s microwave heating, the temperature field was used to update the dielectric properties and then Maxwell's equations were solved to determine electromagnetic power density separately for the discrete frequencies for next rotational state (Pitchai *et al.* 2016). Initial and final temperature of each location were collected for the comparison.

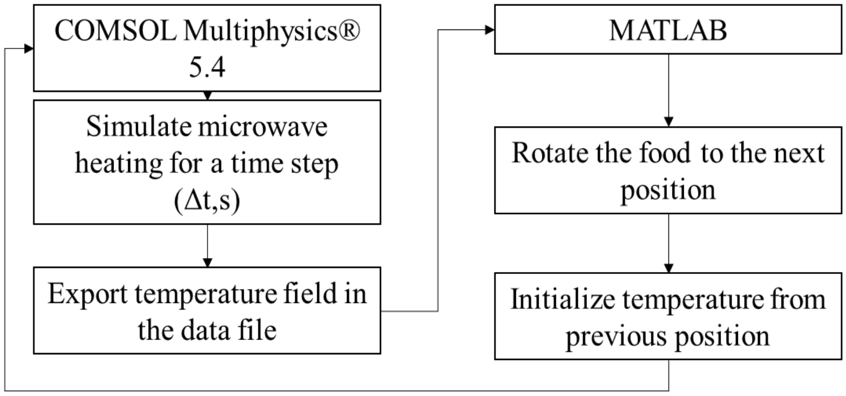

Figure 1. COMSOL-MATLAB interface depicting simulation strategy for rotation food in the turn table.

Inverter heating and cycled heating parameters.

The dielectric properties of mashed potatoes were taken from Chen *et al.* (2013) research. For the cycled heating, the magnetron was set as on for 10 seconds with full power (1200 W) and followed by off for 10 seconds (0 W power), and repeated the power on/off for 6 minutes; while in the inverter heating, the magnetron was set on for the whole 6 minutes heating process with 50% power (600 W). The results of the simulation experiments of 36 different locations of the microwave chamber using cycled and inverter heating were collected.

3. RESULTS AND DISCUSSION

Simulation model development.

Geometry model. Figure 2 shows how the geometric model that COMSOL Multiphysics® 5.4 was able to create in a three-dimensional image with the data entered. This managed to perform a more exact simulation on the parameters to be measured, since each angle and corner of the microwave could be studied in detail. The oven was operating at a 2.45 GHz frequency at rated power of 1200 W. The complete geometric model included oven cavity, magnetron, turntable, waveguide, dents and metal bumps, as shown in figure 2. The magnetron was in the right downside of the cavity. All interior surfaces dimensions were measured and incorporated in the COMSOL Multiphysics® 5.4.

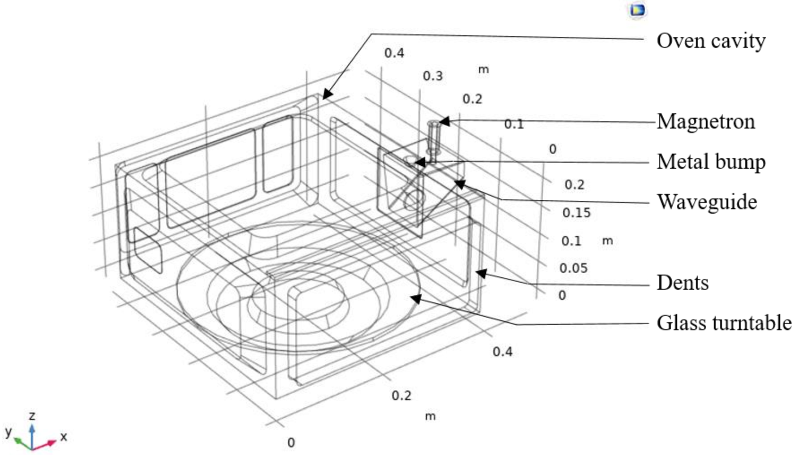

Figure 2. Geometry input in COMSOL Multiphysics® 5.4 (COMSOL Inc., Boston, MA) of the Inverter Panasonic Microwave NN-SN766S.

Three different trays (small rectangular and round tray had 549 cm^3 of volume and big rectangular had 1 098 cm^3) were used for the food product geometries to compare the size and shape in the different models as shown in figure 3. The range of error for each comparison had to be +/- 5%. The results of this study were below this range.

In this study, the simulated round tray volume was 535.8 cm^3 and the real one was 549 cm^3, the validation of the trays were made by using water to measure the volume, which resulted in an error of 3% of complying with the established range. The same process was done with the small and big rectangle tray, both resulted in 2% of error (figure 3).

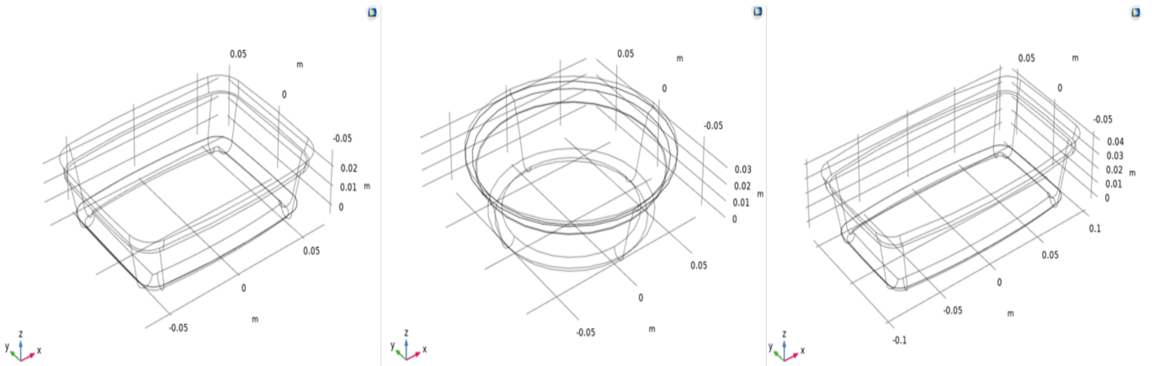

Figure 3. Geometry input in COMSOL Multiphysics® 5.4 (COMSOL Inc., Boston, MA) of the small rectangular, round, and big rectangular trays.

The mesh was the subdivision of the mathematical model into elements with the purpose of setting up and solving a finite element problem. To ensure the simulation results, the mesh modeling was different for each domain. The whole domain consisted of about 231200 tetrahedral elements and 41300 triangles with 0.1028 of minimum element quantity (figure 4), calculated by COMSOL Multiphysics® 5.4. This combination of triangles and tetrahedral elements in the mesh improved a faster solution that is close to the exact solution within some pre-specified error tolerance or other convergence criterion.

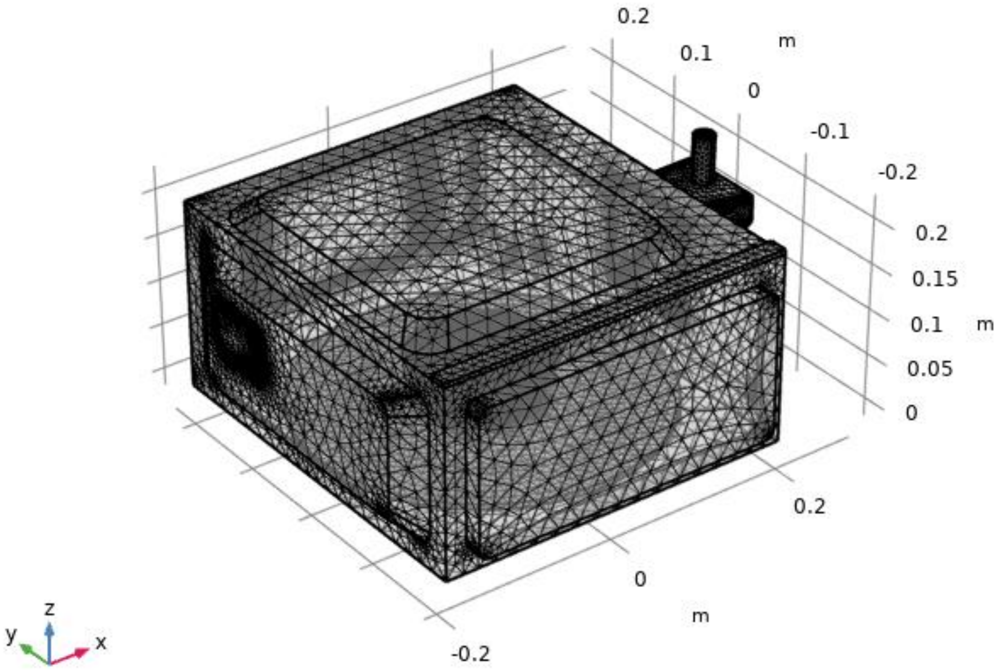

Figure 4. Meshing scheme implemented for the oven cavity and the mashed potatoes in the tray.

Experimental validation.

For the validation of the simulated spatial temperature profile, the small tray was used with mashed potatoes, and compared with the experimental temperature profile obtained using a thermal camera, FLIR C2, of the two replicates.

The thermal images in figure 5 showed that the major portion of the mashed potatoes reached temperatures around 30 °C after 60 s of microwave heating. Similarly, the simulated spatial temperature showed that the higher temperatures, in the range of 21 °C to 90 °C, were located on the edges of the microwave chamber and the temperature on the chamber remained at 30 °C. The maximum temperature in the experimental and simulated experiments were around 90 °C. Overall, simulated spatial temperatures agreed with the experimental thermal images. The two replicates of the temperature profiles showed the same hot regions on the edges of the microwave chamber and the colder ones was in the center. The location of the hot and cold patterns agrees with the ones in the study of Pitchai *et al.* (2016), in which the spatial surface temperature profile between the experiment and simulation was compared using different frequencies for 6 min of heating of frozen mashed potato. To validate the model this method was used in prior studies (Chen *et al.* 2016), in which the simulated and measured top surface temperature distributions were compared after 60 and 120 s of heating; both showed similar heating pattern with the colder region being around the center.

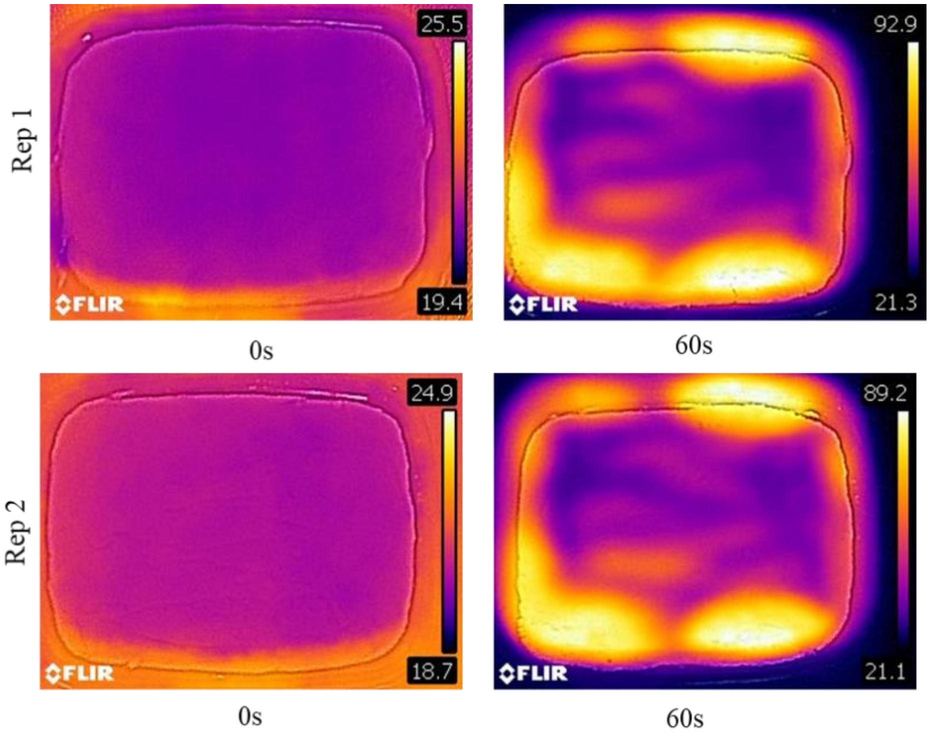

Figure 5. Comparison of spatial temperature profile experiment with simulation subjected to heat in a 1200 W microwave oven using mashed potatoes.

Comparison of inverter heating and cycled heating.

According to the definition of the concept of COMSOL, microwave heating is a multiphysical phenomenon that involves electromagnetic waves and heat transfer; any material that is exposed to electromagnetic radiation will get hot. Electromagnetic waves oscillate inside the oven at a frequency of 2.45 GHz. These fields interact with food, which leads to the generation of calories and an increase in temperature. As reported by Chamchong and Datta (1999), while the power level increases, the surface flow increases in the same proportion. However, in the case of defrosting at higher power levels, external defrosting is relatively faster (Chamchong and Datta 1999).

Defrosting mashed potatoes was done by using two different heating processes, cyclic and inverter. Cyclic heating is considered to be the typical domestic microwave oven whereby microwaves are turned on at full power for a fraction of the time during a cycle followed by zero energies when microwaves are turned off (Chen *et al.* 2015). On the other hand, the inverted microwave oven, its power level can be adjusted according to the heating load taking into account that the magnetron always provides the energy. Kirschner (2009) concluded that inverter technology offers a continuous flow of cooking power, even in lower settings, for precision cooking that preserves the taste and texture of food.

The microwave ovens have a turntable to improve the temperature uniformity of microwave heating (Pitchai *et al.* 2015). In this study, the food in rotation was represent by using 36 locations for each system and container. The result of the average temperature, standard deviation and coefficient of variation (COV) for each location were exported with COMSOL-MATLAB (Fig. 1), thus showing the energy absorption behavior of mashed potatoes. Energy absorption is directly related to the food characteristics that are the dielectric properties, the volume of the food, the shape of the food and the aspect ratio of the food (Zhang and Datta 2001). For this reason, the study evaluated two of these characteristics, shape and size, for the comparison.

The used rectangle (small and big) trays had round edges in the corners, this is because studies had been shown that containers with corners (90° edges, etc.) have a tendency to show localized heating due to the multidirectional distribution of microwave energy (Heddleson and Doores 1994). In addition, the lack of uniformity of energy absorption is manifested in terms of overheating of corners and edges, focusing effects due to curved surfaces of food and resonance within food, in which food behaves like a cavity, with regions of high and low electric fields (Datta and Rakesh 2013).

The comparison of both systems applying different trays resulted in.

Small tray. The simulation of the heating processes using a small rectangular tray resulted in the data showed in figure 6, where it can be observed (figure 6a), that the average temperatures obtained by mashed potatoes during their 6-minute exposure. Since the defrost evaluation was carried out, the initial temperature was set to -10 °C, following the results obtained by Pitchai *et al.* (2015), who modelled microwave heating of frozen mashed potato in a domestic oven incorporating electromagnetic frequency spectrum.

Microwave energy was transformed into heat when absorbed by the mashed potatoes. For the traditional heating process, cycled, the magnetron releases all power for 10 s and then shuts down for another 10 s. This resulted in an undulating behavior that allowed mashed potatoes to increase its temperature in periods of time and decreased it when the microwave was off. On the other hand, in the inverter process a continuous growth of the mashed potatoes temperature was observed (figure. 6a). Both methods, cyclic and inverter, using the small rectangular tray, made the food reach about 32 °C after 6 minutes of exposure.

It is important to emphasize that the temperature had a special behavior at 100 °C. This because according to Chamchong and Datta (1999), a "shield" develops due to a very low depth of microwave penetration on the surface. According to the assumption that once the temperature reaches 100 °C, all the absorbed energy evaporates, and the subsequent temperature is maintained at 100 °C. Therefore, the lack of uniformity begins to decrease. To compare the uniformity of the heating between both methods, the standard deviation and the coefficient of variation were used (figures 6b and 6c). The standard deviation is a measure of non-uniformity, while the COV normalizes the standard deviation by the average temperature, and it was shown to be a more effective measure of non-uniformity (Geedipalli *et al*. 2007). Figures 6b and 6c showed that the heating method in the small tray did not have a significant impact on the heating uniformity since both measures of heating uniformity were almost equal for cyclic and inverted heating These results of the cycled system had similar behavior with the studies of Chamchong and Datta (1999), where they found non-uniformity during thawing at various power cycling and levels.

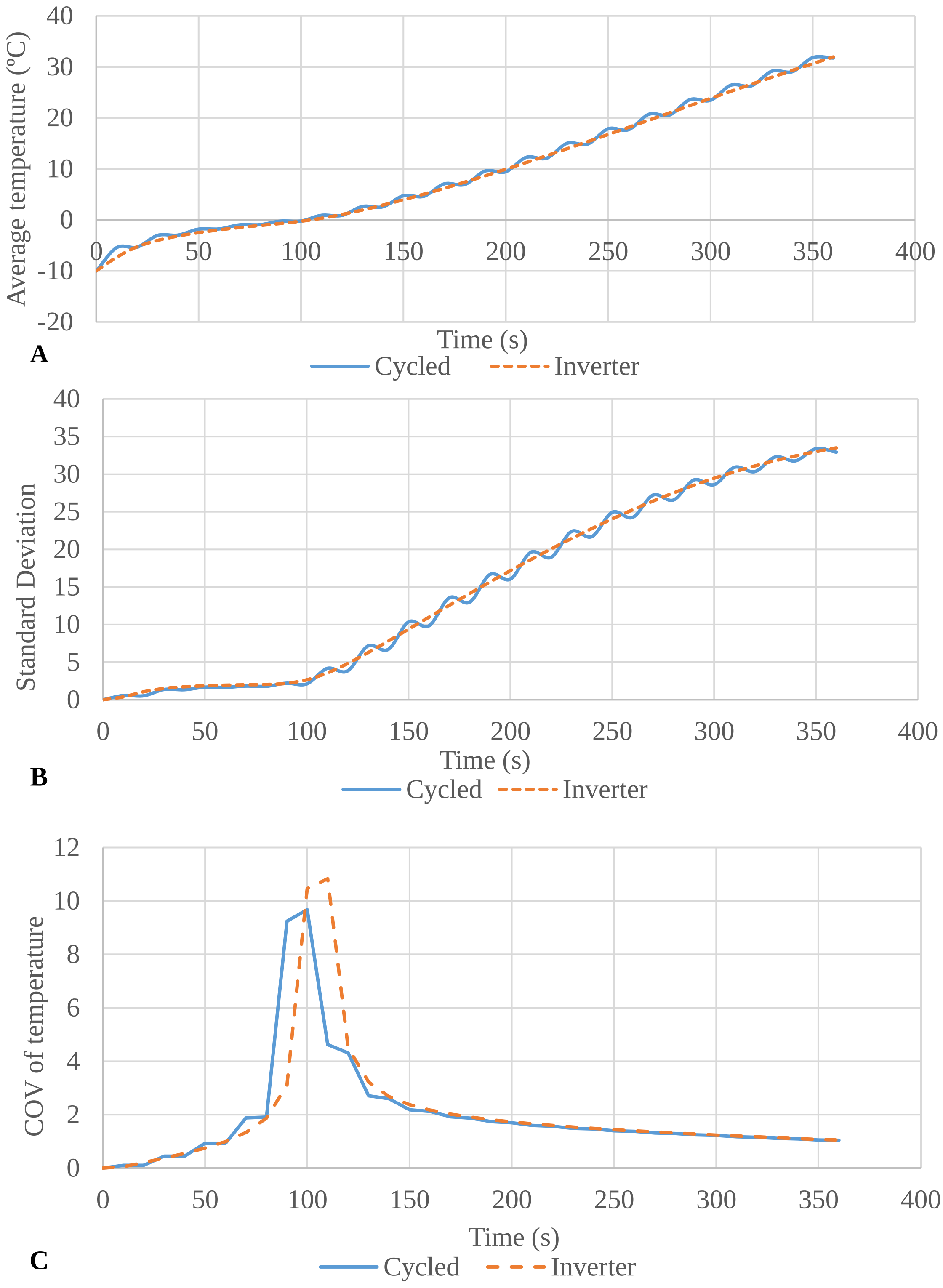

Figure 6. Profile of thawing behavior of frozen mashed potatoes using inverter and cycled heating: A) average temperature; B) standard deviation of temperatures; C) coefficients of variation of temperature of the small rectangle tray filled with mashed potatoes.

Round tray. According to Ibrahim *et al.* (2012), some geometrical forms reflect more microwaves than others. Suggesting package designs that do not have sharp corners and a preference for tubular figures. They also expressed that those foods with packaging that have corners, are designed with metals or aluminum sheets to reflect microwave energy away from the corners and thus selectively heat some more portions.

The use of a round container resulted in the values expressed in figure 7. The first one, figure 7a, represented the temperature profile of the mashed potatoes absorption of the two heating processes. The mashed potatoes temperature progressively increased over time for both heating methods. It can be seen that both, inverter and cycle, had the same temperature profile. But viewed on shorter time scales, the temperature increase was constant for the inverter to warm up, while the cyclic heating method led to faster temperature increases followed by a brief cooling period. The same behavior was reported in the study conducted by Chen *et al.* (2015), for thawing in a microwave cavity.

Despite these temperature variations after the 6 minutes of exposure using both methods, the mashed potatoes reached about ~ 20°C as the average temperature absorbed. For this type of experiments, it was reported that most of the energy was absorbed near the surface (Chamchong *et al.* 1999), which causes a very quick thawing of the boundary and this reduced the penetration depth, which is why the average temperature absorption by the food was not too high.

The uniformity of the energy absorption of the food was obtained using the standard deviation of the average temperatures and the COV (figure. 7b and 7c). Both methods using the round container had similar behavior. In the study by Zhang *et al.* (2018), it was concluded that, if the objective is the uniformity of the temperature of the sample, the spherical shape is the best option. Uniformity is affected since microwave ovens have a special cycle for defrosting food. This is because while the water absorbs the microwaves, the ice does not. Therefore, as the ice melts, the water that forms heat up very quickly and can have very hot ice and water in the same portion of food (Gibbs. 2013). In the study conducted by Gibbs (2013) states that, due to this behavior in the defrosting cycle, microwave power is used as if it were cyclic and it is turned on and off, therefore, there is time for heat to separate from melted water.

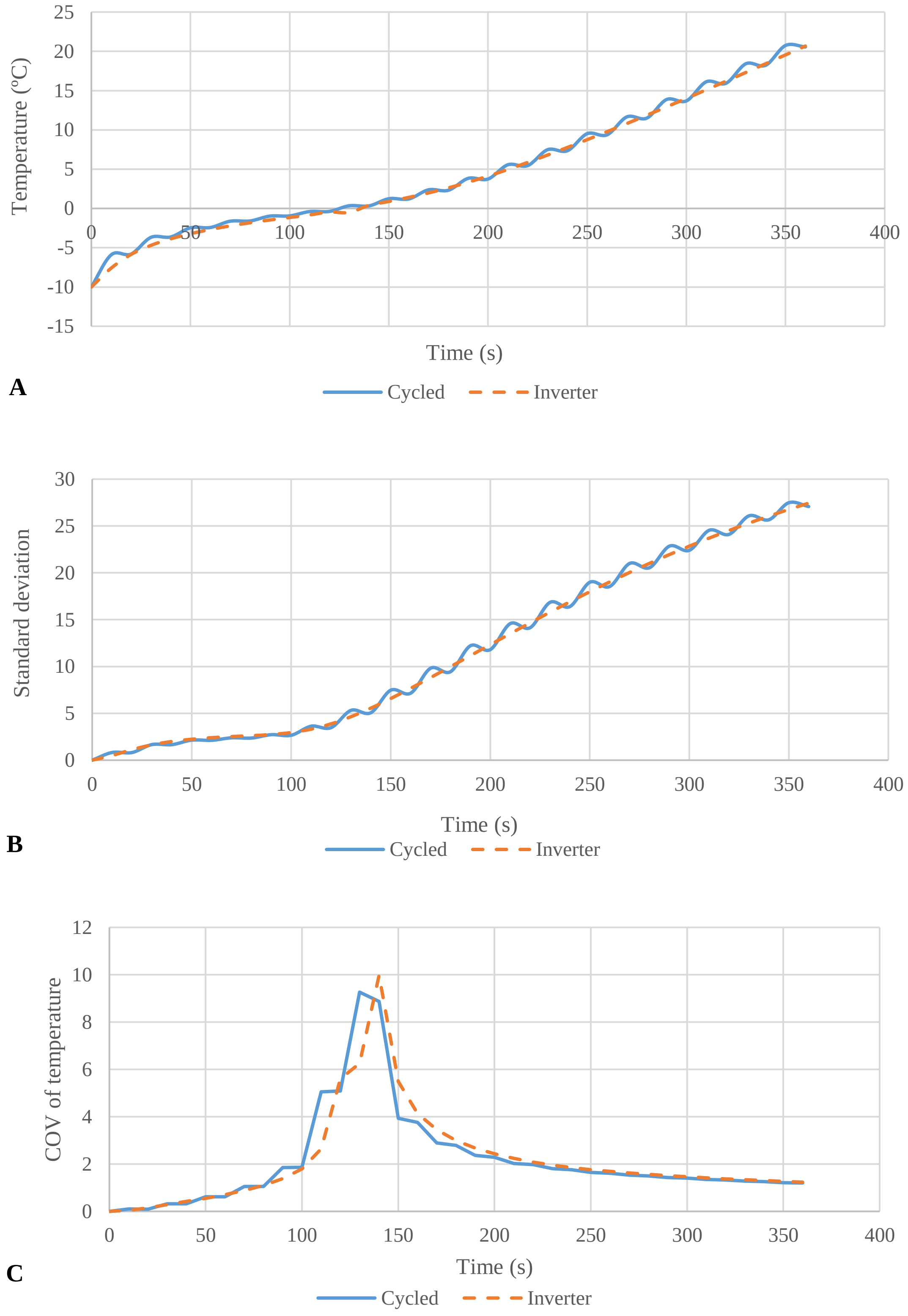

Figure 7. Profile of thawing behavior of frozen mashed potatoes using inverter and cycled heating: A) average temperatures; B) standard deviation of temperatures; C) coefficients of variation of temperature of the round tray filled with mashed potatoes.

Big rectangle tray. The results in figure 8 show the inverted and cyclic heating process. The mashed potatoes placed in a large rectangular tray were exposed for 6 minutes to the cyclic heating method, the magnetron released 1200W periodically. The frequency used was 2.45 GHz in all the exposure. Although, according to Luan *et al.* (2017), the heating patterns of a stationary model food load changed with the varying operating frequency, however, the heating pattern of a rotary model food load was not sensitive to microwave frequencies due to the severe edge heating overshadowing the effects of the frequency variations. The food managed to absorb this energy that was transformed into heat, reaching a final average temperature of approximately ~ 16 °C.

The mashed potatoes heated with the inverter process had an increasing linear behavior, achieving an average temperature of ~ 16 °C, similar to the cyclic process. According to Buffler (1992), the volume of the food (or its volume with respect to the size of the cavity oven) probably has the greatest effect of all food parameters that affect its absorption. The form of power release is important since, according to Chamchong M. and Datta AK. (1999), the defrosting time at higher power levels is considerably reduced, producing initial non-uniform temperature increases, because the surface heats at a faster speed than the interior.

Being a sample with large volume, the absorbed power decreases in the center and increases on the surface, and the radial temperature profiles coincide with the temperature (Romano *et al.* 2005). Uniformity is represented by the standard deviation and the coefficient of variation in figures 8b and 8c, showing that there is no uniformity in the energy absorption of all foods. Zhang *et al.* (2018) stated that in large volume samples, non-uniformity is determined by a COV increase. This may be caused by the shallow penetration of the microwaves in the heated sample. Penetration depth is a useful parameter to quantify the heating efficiency and uniformity of a microwave sample.

Being a sample of mashed potatoes of larger size, it can also be affected by its water content. The composition of food is another factor that determines the absorption of energy released in the microwave. Microwaves are easily absorbed by water, fats and sugars, they can penetrate through most ceramics (Ulaby and Ravaioli 2015).

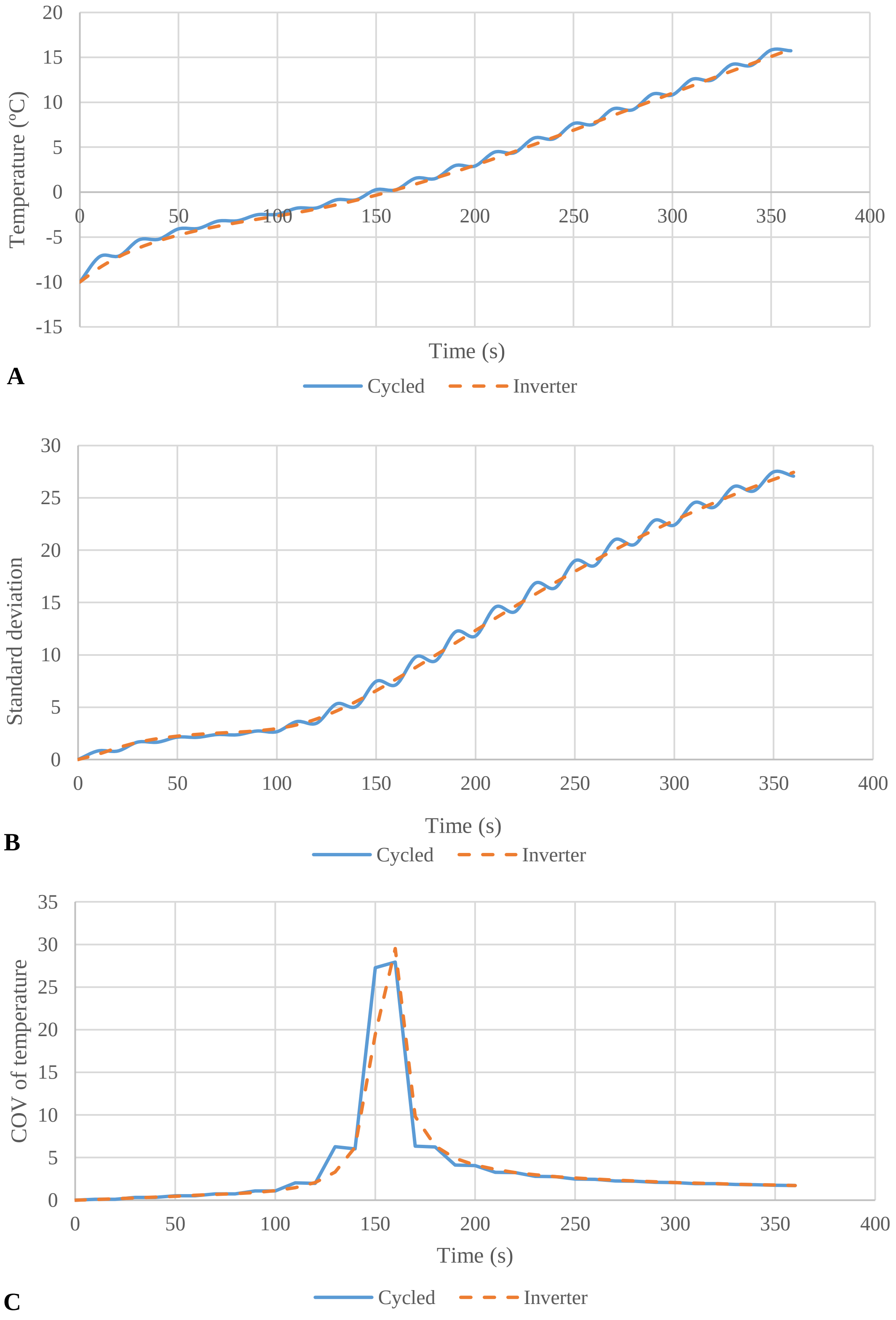

Figure 8. Profile of thawing behavior of frozen mashed potatoes using inverter and cycled heating: A) average temperatures; B) standard deviation of temperatures; C) coefficients of variation of temperature of the big tray rectangle filled with mashed potatoes.

As mashed potatoes is a solid-state food, water molecules are much less mobile, and since it is their movement that causes heat and not vice versa, the effect of microwaves in this case is less. This causes the areas where the water has begun to thaw to be cooked, while others remain in a solid state. figure 9 clearly shows that there is an influence of the size of the tray on the heating profile of the inverter. For the different sizes, the small tray reached the highest temperature (~30 °C) after heating the product for 6 minutes, while the mashed potatoes contained in the large tray did not exceed temperatures above 20 °C. There is a difference of 10 °C from the final heat of small tray and the big one, this is because the wave cannot penetrate the entire product in the same way to allow the molecules to leave and this also depends on the amount of water in the product. The microwaves make the water molecules vibrate, which generates heat; that's why the wet food heat faster than less humid foods, and moist outer layers tend to absorb most of the radiation before they can reach the inner sections, which remain uncooked (FDA 2017).

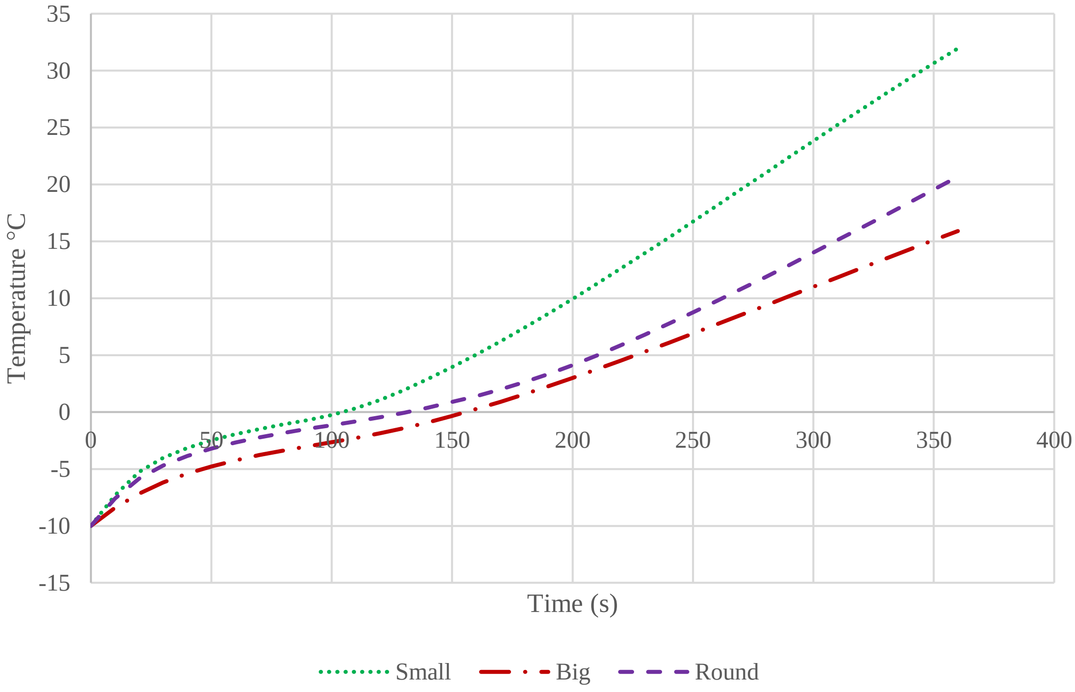

Figure 9. Thawing performance of frozen mashed potatoes using different trays in inverter heating process. Small rectangle tray, big rectangle tray and round tray.

The cyclic method, which is a type of microwave heating method, releases all its power during time changes and this is reflected in the energy absorbed by food and is transformed into heat in an undulating way. figure 10 shows the use of this method in mashed potatoes using different containers. The energy absorption behavior of the food matches that described in the literature (Chen *et al.* 2015). In periods of time, when the magnetron is on, the food absorbs energy and while it is off the food loses some energy.

The size and shape of the food being heated is important in relation to the wavelength and penetration depth. The small rectangular vessel was the one that received the highest energy absorption (~ 30 °C) compared to the large round rectangular one. These results are similar to those reported by Zhang *et al.* (2018), where it was concluded that, if the objective is the uniformity of the temperature of the sample, shapes without borders (round) are the best option, whereas, if the decisive factor is the high capacity of microwave power absorption, the cubic samples are better.

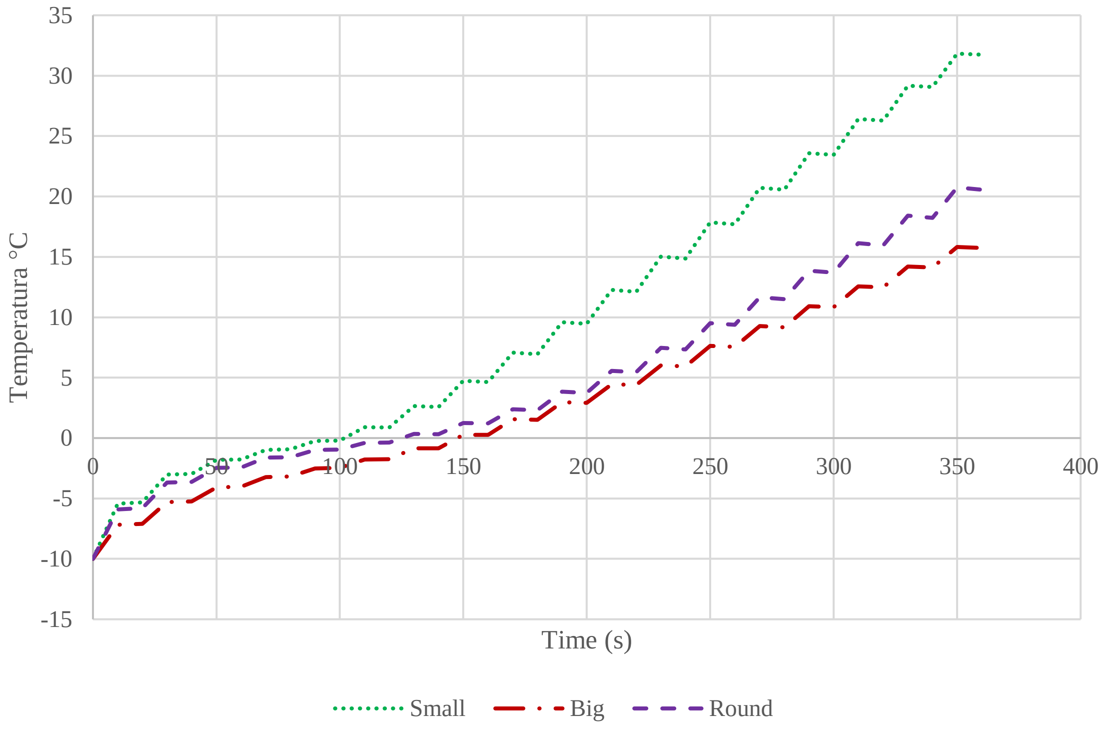

Figure 10. Thawing performance of frozen mashed potatoes using different trays in cycled heating process. Small rectangle tray, big rectangle tray and round tray.

3. CONCLUSIONS

- The simulated model of heating process was developed using COMSOL Multiphysics® 5.4 software, in which the geometry of the microwave had the oven cavity, magnetron, metal bump, waveguide, dents and glass turntable.

- The model of the microwave oven and the different trays were validated and replicates of the temperature profiles showed similar hot regions on the edges of the mashed potatoes with less than 5% of minimum error accepted of difference.

- The thawing temperature profile of each type of tray was not different when evaluated individually in the inverter and cycled heating process, however, when the round, big and small trays where compared only for one type of heating process, the thawing temperature profile differed.

4. RECOMMENDATIONS

- Perform an evaluation not only of the temperature profiles but also the presence of factors such as pathogenic or spoilage microorganisms, insects, and nutrients, among others, in order to know what the effect of dielectric heating has on them.

- Carry on a comparative analysis of the heating processes using a liquid sample since in a solid-state food water molecules are much less mobile.

- Evaluate the dynamic variation of the geometry of the microwave cavity, since this leads to a more uniform distribution of energy in the cooking chamber.

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6. APPENDICES

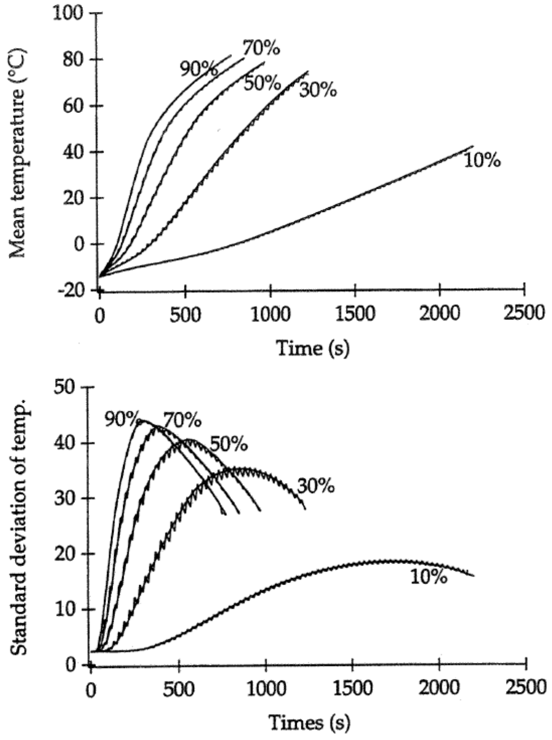
Appendix 1. Panasonic Microwave NN-SN766S.
Source:

Appendix 2. Thermal camera, FLIR C2, Systems, Inc., Portland, USA.
Source:

Appendix 3. COMSOL-MATLAB code simulation strategy for rotation food in the turn table.

```
clear all;
clc;
%addpath('C:\Program Files\COMSOL\COMSOL43a_copy1\mli')
%try
%mphstart('2037')
%catch exception
%end
import com.comsol.model.*
import com.comsol.model.util.*
%ModelUtil.connect('127.0.0.1',9999)

fprintf('Loaded Matlab Script\n');
%model = ModelUtil.create('Model');
fprintf('Created Model object\n');

name='New_Frozen_Rotation_cycled_small_tray';
path=strcat(pwd,'\');   % be careful for "\" at the end of the folder

% show progress
ModelUtil.showProgress(true);

% Start the loop for the geometry parameter:
theta =0;

%Initial temperature


tin= 0;
tlast= 0;
step= 10;
location = 12;
totalheating_time= 360;
Rotation_time = 10; % time for 1 rotation

No_iteration= totalheating_time/step;
dtheta= 360/location;

 for i = 1:ceil(No_iteration)

  %load model file
   model = mphload(strcat('out_',name,'_',num2str(i*step),'.mph'));
fprintf('Loaded Model object\n');

% get average temperature
model.result.numerical.create('av1', 'AvVolume');
model.result.numerical('av1').setIndex('looplevelinput', 'last', 0);
model.result.numerical('av1').selection.set([3]);
model.result.table.create('tbl2', 'Table');
model.result.table('tbl2').comments('Volume Average 1 (T)');
model.result.numerical('av1').set('table', 'tbl2');
model.result.numerical('av1').setResult;
model.result.table('tbl2').save(strcat(path,'\Average_temp.txt'));

AveT =load(strcat(path,'Average_temp.txt'));
   aveT=AveT(:,2);

   if i== 1
      Compile_Ave_T = aveT;

   else
      Compile_Ave_T = cat(2,Compile_Ave_T,aveT);
   end

   dlmwrite(strcat('Ave_Temperature', '.dat'), Compile_Ave_T,
'delimiter', '\t', ...
      'precision', 6)

% get standard deviation
model.result.numerical.create('av2', 'AvVolume');
model.result.numerical('av2').setIndex('looplevelinput', 'last', 0);
model.result.numerical('av2').selection.set([3]);
model.result.numerical('av2').setIndex('expr',strcat('(T-
',num2str(aveT),')^2'), 0);
model.result.table.create('tbl3', 'Table');
model.result.table('tbl3').comments(strcat('Volume Average 2 ((T-
(aveT))^2)'));
model.result.numerical('av2').set('table', 'tbl3');
model.result.numerical('av2').setResult;
model.result.table('tbl3').save(strcat(path,'\Std_T.txt'));

STDT =load(strcat(path,'Std_T.txt'));
   stdT=STDT(:,2);

   if i== 1
      Compile_std_T = stdT;

   else
      Compile_std_T = cat(2,Compile_std_T,stdT);
   end


   dlmwrite(strcat('Std_Temperature', '.dat'), Compile_std_T,
'delimiter', '\t', ...
      'precision', 6)

end
```

Appendix 4. Mean temperature profile and non-uniformity during thawing at various power cycling and levels.
Source: Chamchong M. and Datta AK. 1999



Appendix 5. Surface after 10 s microwave heating mashed potatoes.
Source: Chen *et al.* 2014.