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Optimization of pulsed microwave heating

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Abstract

A simulation model was used to optimize pulsed microwave heating of precooked mashed potato cylinders of 82.7% moisture content. The experimental variables were: (1) sample radius: 2.4, 2.8 and 3.2 cm (or 1.5, 1.75 and 2.0 times the penetration depth of microwave radiation), (2) temperature rise during microwave power-on constraint (ΔT_{on}): 20 and 15 °C, (3) temperature drop during microwave power-off constraint (ΔT_d): 5 and 3 °C lower than ΔT_{on}, (4) total processing time (<1000 s) and (5) average sample temperature (60 °C). The evaluation showed that the 2.4–2.8-cm radius samples were heated uniformly and efficiently. The ΔT_{on} constraint is very critical for optimum pulsed microwave heating; $\Delta T_{on} = 20$ °C was a better choice than $\Delta T_{on} = 15$ °C. ΔT_d constraint affects the total processing time for a large sample more significantly than for a small sample. The total processing time depends on ΔT_{on}, ΔT_d, and sample radius. In the case of 2.4-cm radius samples (1.5 times the penetration depth) with $\Delta T_{on}(\Delta T_d) = 20(3)$ °C constraint, the pulsed microwave energy can heat the mashed potato sample to an average temperature of 60 °C in 336 s. This was the most efficient process among all evaluated conditions with respect to total processing time.

Keywords: Penetration depth; Power consumption; Pulsed microwave; Optimization; Temperature profile

1. Introduction

The advantages of intermittent drying – drying with rest periods – have been well established for a variety of materials with or without microwave energy (Farkas & Rendik, 1997; Harnoy & Radajewski, 1982; Langrish, Keey, & Kumar, 1992; Shivhare, Raghavan, Bosisio, & Mujumdar, 1992). Carroll and Churchill (1986) reported that intermittent on–off heating with fixed heat flux density is particularly advantageous when deep and rapid penetration of energy is to be accomplished while constraining the maximum temperature at the surface. Further, intermittent heating reportedly results in greater depth of heating than continuous heating for the same total heat input. During microwave heating, pulsed application of energy – i.e., turning the magnetron power "on" and "off" intermittently – leads to more uniform temperature distribution within the sample than during continuous application of energy (Yang & Gunasekaran, 2001, 2004). This is due to thermal energy equalization via conduction from hot to cold region during the power-off periods. This leads to improved product quality and process efficiency (Gunasekaran, 1999; Youngsawatdigul & Gunasekaran, 1996). However, to optimize the pulsed microwave heating process, certain parameters should be constrained.

Penetration of microwave energy inside a material is a function of its dielectric properties, which can alter the temperature distribution (TD) within the sample. As the sample size increases, the sample regions away from the surface are not heated satisfactorily due to decaying microwave energy as it propagates into the sample. Pollak and Foin (1960) reported, in a microwave-heated beef cylinder (radius = 6 cm, penetration depth, $D_p = 2.1$ cm), temperature at the center was lower than at the surface. For a small sample (relative to microwave penetration depth), focusing effect of microwave energy accumulates as a function of time and causes overheating at the sample center. The

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pulsed heating is especially suitable for such cases. Therefore, sample dimension and heating time should be optimized to prevent overheating and underheating during pulsed microwave processing of foods.

The objective of this study was to evaluate the effect of different levels of processing parameters on temperature uniformity in a microwave-heated food. Precooked mashed potato was used as the sample food material. The parameters studied were sample dimension, sample temperature distribution, processing time, and power level.

2. Materials and methods

2.1. Sample preparation

Mashed potato flakes (Idaho Spuds, The Pillsbury Company, Minneapolis, MN) were purchased from a local supermarket. Mashed potato was prepared according to the manufacturer's directions but without suggested butter and salt addition. Distilled water (1800 mL) was brought to a rolling boil and potato flakes (370 g) were stirred in with a hand mixer (KitchenAid KHM-7) at the lowest speed (250 rpm), to a uniform consistency. The mashed potato samples were transferred into 4- and 2.4-cm radius glass beakers to a height of 7 cm and covered with waxed paper to prevent moisture loss. They were stored in a refrigerator at 4 °C for at least 16 h to ensure sample temperature uniformity before microwave heating experiments.

2.2. Physical and dielectric properties

Sample moisture content was determined in triplicate by an infrared moisture analyzer (LJ 16 Mettler Toledo Inc, Switzerland) with a set temperature of 160 °C. About two grams of sample was placed in the moisture analyzer. Sample mass was measured by a built-in digital balance capable of reading to four decimal places during the infrared heating. Sample moisture content was automatically calculated by the moisture analyzer. The measurement was terminated if, after three consecutive 10-min intervals, the moisture content varied less than ±0.2%.

Thermal and dielectric properties of the mashed potato were determined using moisture content dependent models available in the literature. The models and corresponding property values used are summarized in Table 1.

2.3. Microwave heating

A laboratory microwave oven which operates at 2.45 GHz (Labotron 500, Zwag Inc., Epone, France) was used. It has two selectable continuous output power settings of 250 and 500 W. The oven cavity is 33 × 22 × 35 cm (width × height × depth) and houses a 25 × 3.5 cm (diameter × height) turntable that rotates at 15 rpm.

The sample along with the glass beaker was placed at the center of the turntable in the oven cavity and heated for 1 min at 250-W oven setting. Sample temperature distribution (TD) was measured across the horizontal mid-plane at radial distances of 0, 1, 2, 3, and 4 cm from the sample center. A fine wire (0.82-mm diameter) type-T thermocouple connected to a data logger was used for temperature measurement at the end of one-minute heating.

A numerical model developed using Maxwell's equation was used to simulate temperature distributions in the sample. The details of this model have been presented

Table 1
Thermal and dielectric properties of mashed potatoes with 82.7% moisture content (M, %) and different temperatures (T, °C)

Parameter	Model	Temperature (°C)	Value
Thermal conductivity, W/m^2 °C	$0.00493M + 0.148$ [a]		0.55
Specific heat capacity, J/g °C	$33.3M + 833.3$ [b]		3,587
Dielectric constant	$2.14 - 0.104T + 0.808M$ [c]	4	68.4
		10	67.8
		20	66.7
		30	65.7
		40	64.6
		50	63.6
		60	62.6
		70	61.5
Dielectric loss factor	$3.09 - 0.0638T + 0.213M$ [c]	4	20.4
		10	20.0
		20	19.4
		30	18.7
		40	18.1
		50	17.5
		60	16.8
		70	16.2

[a] From Sweat (1974).
[b] From Mohsenin (1980).
[c] From Calay et al. (1995).

previously (Yang & Gunasekaran, 2004). This model was used without power correction for evaporative cooling because the samples were not exposed to air.

2.4. Analysis of optimal process

The pulsed microwave heating is most effective for samples with hot spots around their centers, i.e., when the sample center temperature tends to be significantly higher than that of the surrounding material. In such cases, equalization of thermal energy due to conduction during microwave power-off periods tends to result in a more uniform temperature profile across the sample. Therefore, to study optimization of pulsed microwave heating using mashed potato as the example food, sample radius should be less than 4 cm (2.5 D_p) and comparable to D_p. Accordingly, sample radii of 1.6, 2.4, 2.8 and 3.2 cm (or 1, 1.5, 1.75 and 2 D_p) were considered. All samples were 7-cm high.

Continuous microwave heating was simulated for 30 s (using the model developed based on Maxwell's equations). The center temperature in the 1.6-cm radius sample was the highest and is an excellent candidate for illustrating the temperature equalization under pulsed microwave heating. However, 1.6-cm radius sample was considered too small to be practical. Thus, 2.4, 2.8 and 3.2-cm radius samples were considered for further analyses using the following criteria:

1. Initial sample temperature is 4 °C.
2. Microwave energy (at 250-W oven setting) is applied continuously until the maximum temperature difference between any two measured locations (ΔT_{on}) in the sample just exceeds 15 and 20 °C.
3. This is followed by a power-off period until the temperature drop during the power-off period (ΔT_d) exceeds by 3 and 5 °C (i.e., maximum temperature difference at any two measured locations in the sample is 12 and 10 °C for $\Delta T_{on} = 15$ °C, and 17 and 15 °C for $\Delta T_{on} = 20$ °C).
4. Total processing time (power-on time plus power-off time) should be less than 1000 s.
5. Maximum sample temperature anywhere should not exceed 70 °C, because the predictive dielectric property models we used (Table 1) are valid only between 0 and 70 °C.
6. If necessary, 500-W oven setting can be used to satisfy some constraints.

To facilitate easy evaluation of simulated data the numerical model based on Maxwell's equations was modified as follows (Yang, 2002):

1. Automatically calculate sample average, maximum, and minimum temperatures.
2. Each power-on period continues until maximum and minimum sample temperature differential exceeds the set criterion, then it was followed by a power-off period.
3. Each power-off period continues until interior temperature differential decreases to the set criterion.
4. At end of each power-off period, dielectric properties are evaluated according to average sample temperature.
5. Conditional loops repeat the computations until power-on or power-off temperature differential or time limit (1000 s) is reached.

3. Results and discussion

The temperature distribution (TD) measured in the 4-cm diameter sample is presented in Fig. 1 along with the corresponding values calculated using Maxwell's model. The measured and predicted TDs agreed well validating the use of the model for heating precooked mashed potato cylinders. Temperature generally decreased from the surface to center. This is because the penetration depth (D_p) of microwaves is 1.6 cm for the mashed potato sample (82.7% moisture content, 4 °C). The D_p is calculated as follows:

$$D_p = \frac{\lambda_0}{\sqrt{2}\pi\left[\kappa'(\sqrt{1+\tan^2\delta}-1)\right]^{1/2}},$$

where λ_0 is incident wavelength (12.24 cm), κ' is dielectric constant (68.4), δ is loss angle (0.29 rad). Further validation of the model is presented in Fig. 2 in which very good agreement between simulated and measured TD for 2.4-cm radius sample is presented. In addition, simulated data for 1.6, 2.8, and 3.2-cm radius samples presented in Fig. 2 clearly indicate the effect of sample size. For small samples (1.6-cm radius), the center temperature was excessive.

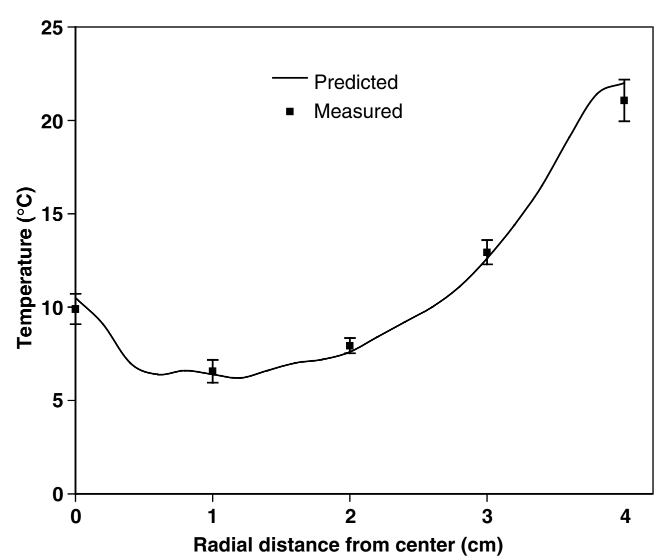

Fig. 1. Measured and predicted temperature profiles in a 4-cm radius mashed potato cylinder after 1 min of continuous microwave heating at the 250-W oven setting.

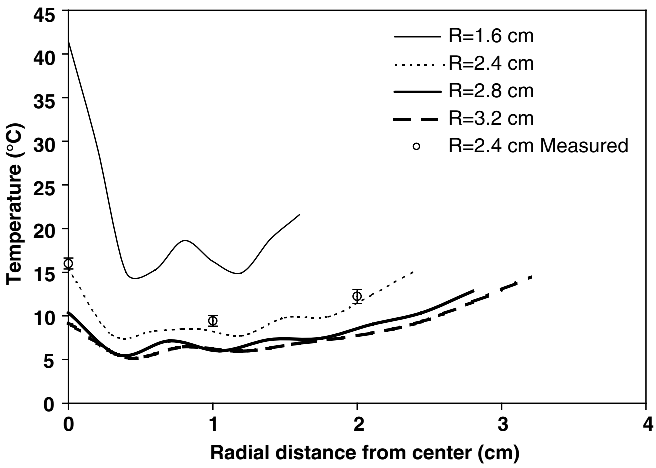

Fig. 2. Predicted temperature profiles in 1.6-, 2.4-, 2.8- and 3.2-cm radius mashed potato cylinders after 30 s of microwave heating at the 250-W oven setting. Measured data for 2.4-cm radius sample is also shown.

4. Optimization analysis

Results of optimization analysis using pulsed microwave power at 250-W oven setting are shown in Figs. 3–5 for 2.4-, 2.8- and 3.2-cm radius samples, respectively. At the beginning, heating rate is the greatest because microwave energy was applied continuously. The time of continuous power application (at the beginning of simulation) for $\Delta T_{on} = 20$ °C is longer than $\Delta T_{on} = 15$ °C and resulted in higher average sample temperatures. When $\Delta T_{on} = 20$ °C, the total processing time was shorter than for $\Delta T_{on} = 15$ °C.

The power-on (PO) to total processing (TP) time ratios under $\Delta T_{on} = 20$ °C and $\Delta T_{on} = 15$ °C conditions with $\Delta T_d = 5$ °C at the same average sample temperature were calculated (Table 2). The PO/TP ratios are higher for $\Delta T_{on} = 20$ °C than for $\Delta T_{on} = 15$ °C condition. This is because of longer PO and shorter TP for $\Delta T_{on} = 20$ °C. The penetrating nature of microwaves causes an uneven power distribution in the material. As heating time

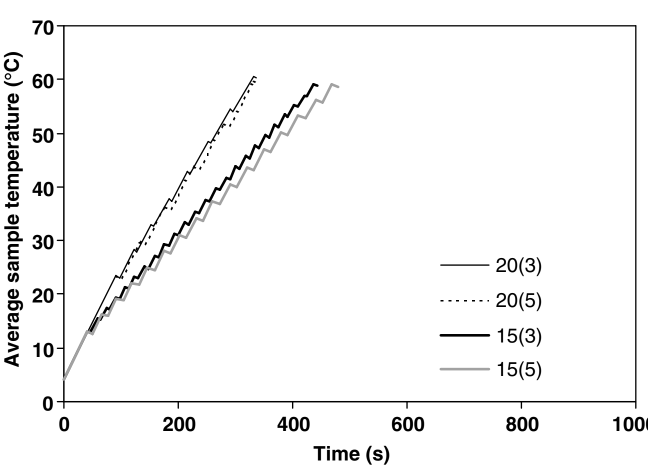

Fig. 3. Average sample temperature profiles in 2.4-cm radius, 7 cm-long, mashed potato cylinders heated by pulsed microwave at the 250-W oven setting. Temperature rise during power-on constraints (ΔT_{on}) were 20 and 15 °C and temperature drop during power-off constraints (ΔT_d) were 5 and 3 °C (i.e. $\Delta T_{on}(\Delta T_d) = 15(5)$, 15(3), 20(5) and 20(3)).

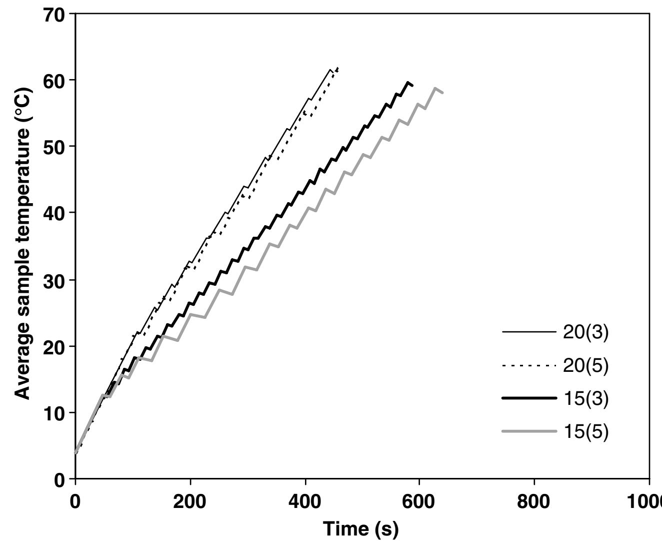

Fig. 4. Average sample temperature profiles in 2.8-cm radius, 7-cm long, mashed potato cylinders heated by pulsed microwave at the 250-W oven setting. Temperature rise during power-on constraints (ΔT_{on}) were 20 and 15 °C and temperature drop during power-off constraints (ΔT_d) were 5 and 3 °C (i.e. $\Delta T_{on}(\Delta T_d) = 15(5)$, 15(3), 20(5) and 20(3)).

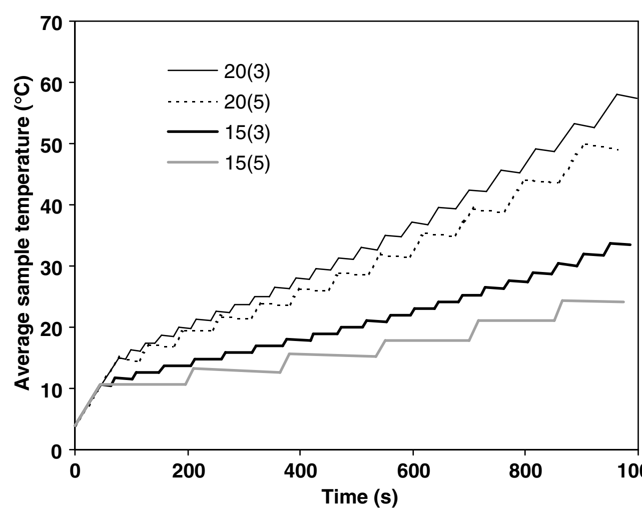

Fig. 5. Average sample temperature profiles in 3.2-cm radius, 7-cm long, mashed potato cylinders heated by pulsed microwave at the 250-W oven setting. Temperature rise during power-on constraints (ΔT_{on}) were 20 and 15 °C and temperature drop during power-off constraints (ΔT_d) were 5 and 3 °C (i.e. $\Delta T_{on}(\Delta T_d) = 15(5)$, 15(3), 20(5) and 20(3)).

Table 2
Power-on (PO) to total processing (TP) time ratios under the $\Delta T_{on}(\Delta T_d) = 20(3)$ °C and $\Delta T_{on}(\Delta T_d) = 15(3)$ °C constraints at different final average sample temperature (T_{fas}, °C)

Radius (cm)	2.4	2.8	3.2
PO/PT at ΔT_{on}:$T_{fas} = 20:60$	0.88	0.66	0.43
PO/PT at ΔT_{on}:$T_{fas} = 15:30$	0.67	0.47	0.22

progresses, non-uniform TD in the sample becomes more pronounced. It can be resolved by setting proper power-on temperature constraint. In the case of $\Delta T_{on} = 15$ °C, it obviously takes less time to heat the sample from the starting point of the cycle than it does to heat the same sample to $\Delta T_{on} = 20$ °C. However, energy needed to heat the sample under $\Delta T_{on} = 20$ °C constraint is greater than that under $\Delta T_{off} = 15$ °C constraint. The temperature gradient within the sample, which is the driving force for sample temperature equalization, is greater under $\Delta T_{on} = 20$ °C condition. Therefore, under $\Delta T_{on} = 20$ °C constraint, the on–off cycle is shorter than under $\Delta T_{on} = 15$ °C constraint.

The power-off temperature differences (ΔT_d) were 5 and 3 °C. Generally, the larger the ΔT_d, the longer the total processing time needed to achieve the same average sample temperature. For the case of $\Delta T_{on} = 20$ °C and sample radius = 2.4 cm (1.5 D_p), there is only small difference between $\Delta T_d = 5$ and 3 °C constraints with respect to time-dependent average sample temperature curves (Fig. 3). As sample radius increased, the difference became larger (Figs. 4 and 5), and was dependent on ΔT_{on} constraint.

For sample radius of 2.4 cm (1.5 D_p) with $\Delta T_{on}(\Delta T_d) =$ 20(3) °C constraints, final sample average temperature (T_{fsa}) can reach around 60 °C in 336 s. For sample radii of 2.8 and 3.2 cm (1.75 and 2 D_p), all other parameters remaining the same, $T_{fsa} = 60$ °C was achieved at 449 and 997 s, respectively. Fig. 6 shows sample TD after microwave heating under $\Delta T_{on}(\Delta T_d) = 20(3)$ °C constraints. Under $\Delta T_{on}(\Delta T_d) = 15(3)$ °C constraints, it took too long to heat the sample to average temperature of 60 °C (443 and 586 s for 1.5-D_p and 1.75-D_p radius samples, respectively). Under $\Delta T_{on}(\Delta T_d) = 15(3)$ °C constraints, average temperature of a 3.2-cm (2-D_p) radius sample did not reach 60 °C within the preset 1000 s maximum processing time constraint. All simulation results showed that the sample can be heated to an average temperature of about 30 °C. However, the larger the sample radius, the longer the difference in total processing time between $\Delta T_{on}(\Delta T_d) = 15(5)$ and 20(5) °C constraints. The microwave pulsing sequences are consistent for 2.4 and 2.8-cm (1.5- and 1.75-D_p) radius samples. The heating time sequences that can be applied to samples to obtain final average temperature of 60 °C and satisfy $\Delta T_{on}(\Delta T_d) = 20(3)$ °C criteria are listed in Table 3. For the 3.2-cm (2-D_p) radius sample, longer power-off periods are needed because temperature is higher at the surface than at the center (Fig. 6). Therefore, pulsed microwave application is not as beneficial for 3.2-cm radius samples as it is for 2.4 and 2.8-cm radius samples. Accordingly, it may be concluded that pulsed microwave application is most effective when the critical sample size (radius) is less than 2 D_p.

The use of 500-W oven setting was also simulated for heating 3.2-cm radius sample and the result was compared to that obtained at the 250-W oven setting under $\Delta T_{on}(\Delta T_d) = 20(3)$ constraint (Fig. 7). As expected, TP was shorter at 500-W setting than at 250-W setting for attaining sample average temperature of 60 °C.

The above analysis can be extended to optimize total power consumption by suitably constraining the process parameters for a given sample size.

Table 3
Microwave pulsing sequences applied to 2.4- and 2.8-cm radius samples which comply the $\Delta T_{on}(\Delta T_d) = 20(3)$ °C criteria

Radius (cm)	(Time interval):pulsing ratio:number of duty cycles	
2.4	(0–92):1:1	(92–336):1.17:7
2.8	(0–108):1:1	(108–449):2.2:10

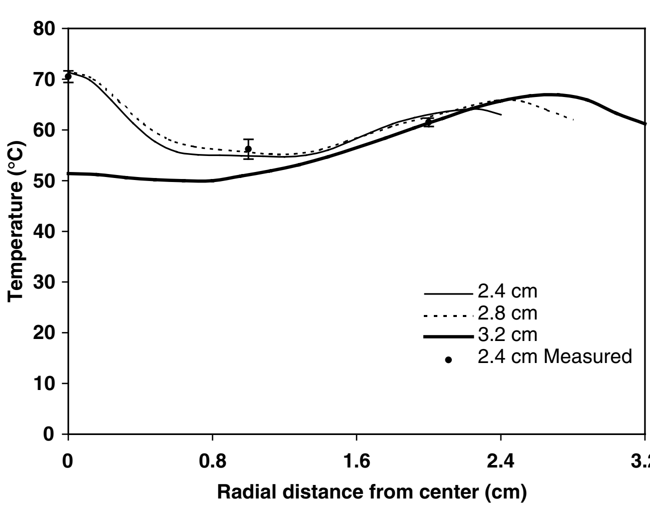

Fig. 6. Temperature distribution in 2.4, 2.8 and 3.2-cm radius potato cylinders under the temperature rise during power-on constraint (ΔT_{on}) of 20 °C and temperature drop during power-off constraint (ΔT_d) of 3 °C (i.e., $\Delta T_{on}(\Delta T_d) = 20(3)$) average sample temperature is about 60 °C at the 250-W oven setting.

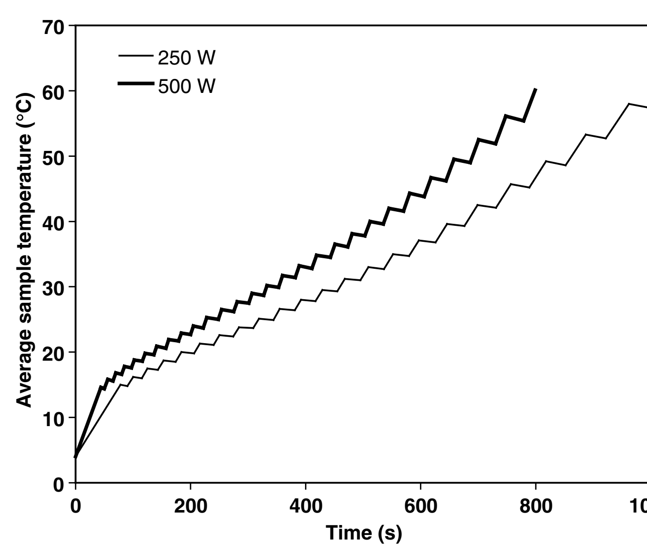

Fig. 7. Time and average sample temperature of a 3.2-cm mashed potato cylinder under temperature rise during power-on constraint (ΔT_{on}) of 20 °C and temperature drop during power-off constraint (ΔT_d) of 3 °C (i.e., $\Delta T_{on}(\Delta T_d) = 20(3)$) at the 250 and 500-W oven settings.

5. Conclusions

Pulsed microwave heating is most effective when sample radius is $\leqslant 2\,D_p$. Maximum microwave power-on and power-off temperature constraints are very critical for optimal application of pulsed microwave heating. Power-on temperature constraint produces suitable temperature gradient. Power-off temperature constraint allows the temperature equalization to occur. The power-off temperature constraint affects the total processing time as the sample radius increases. The most efficient process among all the cases considered is the heating of 2.4-cm (1.5-D_p) radius precooked mashed potato sample under the $\Delta T_{on}(\Delta T_d) = 20(3)$ °C constraint.

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