Preliminary study of surface temperature distribution during microwave heating of cereals and oilseed

R. Vadivambal[1], D.S. Jayas[1]*, V. Chelladurai[1] and N.D.G. White[2]

[1]*Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, R3T 2N2 Canada; and* [2]*Cereal Research Centre, Agriculture and Agri Food Canada, Winnipeg, Manitoba, Canada. *E-mail: digvir_jayas@umanitoba.ca*

Vadivambal, R., D.S. Jayas, V. Chelladurai and N.D.G. White. 2009. **Preliminary study of surface temperature distribution during microwave heating of cereals and oilseed**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 51: 3.45–3.52.
The major drawback associated with microwave heating is the non-uniform temperature distribution. Temperature distribution studies have shown that various materials behave differently during microwave heating. A pilot-scale industrial microwave dryer operating at 2450 MHz was used to heat grains and oilseed. An infra-red thermal camera was used in this study to determine the temperature distribution in bulk rye and oats at 14, 16, and 18% moisture content (wet basis) and sunflower seeds at 8, 10, and 12% moisture content after being heated in the microwave drier. Fifty grams of grain were placed in a sample holder and allowed to pass on a conveyor belt under the applicator at 0, 200, 300, 400, and 500 W for 28 or 56 s. There were hot and cool regions in the samples. The temperature difference between hot and cool regions in a given sample varied between 23 and 62°C for rye, 7 and 25°C for oats and 7 and 29°C for sunflower seeds. The preliminary results of this study suggest that while using microwave as a heat treatment, the maximum temperature that can affect seed viability (potential to germinate under favorable conditions) should be taken into consideration, when developing microwave processing systems for grains and oilseeds.
Keywords: microwave, thermal images, rye, oats, sunflower seeds, temperature distribution.

Le désavantage principal du chauffage aux micro-ondes est la distribution non uniforme de la température. Des études de distribution de température ont montré que plusieurs matériaux se comportent de manière différente durant le chauffage aux micro-ondes. Dans cette étude, un séchoir à micro-ondes expérimental de type industriel fonctionnant à 2 450 MHz a été utilisé pour chauffer des grains et des oléagineux. Une caméra thermique à l'infrarouge a été utilisée pour déterminer la distribution de la température dans du seigle et de l'avoine en vrac à des teneurs en eau de 14, 16 et 18% (base humide) ainsi que des graines de tournesol à des teneurs en eau de 8, 10 et 12% après avoir été chauffés dans le séchoir à micro-ondes. Cinquante grammes de grains ont été mis dans un contenant placé sur un convoyeur à courroie pour être exposés à une puissance de chauffage de 0, 200, 300, 400 et 500 W pendant 28 ou 56 s. Les échantillons ainsi traités présentaient des zones chaudes et fraîches. Les différences de température entre les zones chaudes et fraîches ont varié entre 23 et 62°C pour le seigle, 7 et 25°C pour l'avoine et 7 et 29°C pour les graines de tournesol. Ces résultats préliminaires suggèrent que lors d'un traitement de chauffage par micro-ondes la température maximale qui peut affecter la viabilité des grains (potentiel de germination sous des conditions favorables) devrait être prise en considération lorsque des systèmes de traitement par micro-ondes sont développés pour les grains et les oléagineux.
Mots clés: micro-ondes, images thermiques, seigle, avoine, graines de tournesol, distribution de température.

INTRODUCTION

Microwave heating is gaining popularity as an alternative to conventional methods of heating. Temperature distribution and heating pattern is different in microwave heating compared with conventional heating. In conventional heating, the product is exposed to high temperature for a long time, which may result in the degradation of the quality of the heated product. Conventional heating occurs by convection followed by conduction within the product where heat must diffuse in from the surface of the material. In microwave heating, heat is generated throughout the material, leading to faster heating rates (Gowen et al. 2006).

Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting polar molecules of a material (Mullin 1995). When an electric field is applied, the bipolar molecules tend to behave like microscopic magnets and attempt to align themselves with the field. When the electrical field is changing millions of times per second (915 or 2450 million times per second), these molecular magnets are unable to keep up the forces acting to slow them. This resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation. Microwave fields are a form of energy, and microwaves are converted to heat by their interaction with charged particles and polar molecules, their agitation is defined as heat (Buffler 1993).

Microwave heating is characterized by rapid volumetric heating resulting in a high thermal efficiency, shorter drying time and improved product quality (Prabhanjan et al. 1995). Microwave drying requires a smaller floor space compared with conventional driers because the increase in processing rate makes it possible to design more compact equipment, and hence plant capacity can be increased without additional building space. Fast start-up and shut-down and precise process control are possible

during microwave heating (Mullin 1995). Microwave drying is most effective at product moisture contents below 20%; therefore, it has been suggested that microwave energy should be applied in the falling rate period or at low moisture content to finish drying (Maskan 2000). At low moisture content, the removal of moisture with microwave heating is much faster than when using hot air due to its volumetric heating and energy transfer mechanism (Mullin 1995).

The inherent problem associated with microwave heating is the non-uniformity of temperature distribution in microwave-heated foods and grains. The temperature distribution during microwave heating was studied by many researchers (Burfoot et al. 1988; Fakhouri and Ramaswamy 1993; Mullin and Bows 1993; Ryynanen and Ohlsson 1996; Goksoy et al. 1999; Ryynanen et al. 2001; Lee et al. 2002; Sakai and Wang 2004; Manickavasagan et al. 2006a; Gunasekaran and Yang 2007; Geedipalli et al. 2007). Goksoy et al. (1999) used fibre optic probes to monitor temperature changes during microwave heating. Burfoot et al. (1988) studied the temperature distribution in microwave pasteurization of prepared meals by using thermocouples at the corners and at the centre of the product. Mullin and Bows (1993) studied the temperature distribution in frozen ready-to-eat meals and mashed potatoes using fibre optic probes and compared it with thermal imaging. Many researchers have used thermocouples and fibre optic sensors for measuring temperature distribution. With thermocouples and fibre optic probes, temperatures were measured only at certain points in the sample, which might not have given a complete temperature distribution pattern.

Thermal imaging is a non-destructive infrared imaging technique that measures the infrared energy emitted from the object surface (Varith et al. 2003). All objects with a temperature greater than absolute zero (-273°C) emit infrared radiation and the total amount of radiation emitted from the object is related to its temperature. The non-contact thermal imaging method is used to map the surface temperature of the object in two dimensions at a high resolution (Manickavasagan et al. 2006b).

Although temperature distribution during microwave heating has been widely studied, not many published results are available on microwave heating of grain. Manickavasagan et al. (2006a) studied the temperature distribution and determined the non-uniform surface temperatures in wheat, barley, and canola. Their study has shown that there were hot and cool spots on the microwave heated grain and the grain type had a significant effect on the surface temperature. Since each grain type had a significant effect on the temperature distribution during microwave heating and as there was no published literature available on temperature distribution in many cereals and oilseeds, the objective of our study was (1) to determine the surface temperature distribution of microwave-heated bulks of rye, oats, and sunflower seeds using an infra red thermal camera, (2) to determine the maximum and minimum temperatures of the rye, oats and sunflower bulk samples heated with microwaves at different power levels and exposure times, and (3) to determine the moisture loss during microwave heating in rye, oats, and sunflower seeds.

MATERIALS and METHODS

Grain samples

The rye (*Secale cereale* L.) cultivar Musketeer, oats (*Avena sativa* L.) cultivar AC Marie and sunflower (*Helianthus annuus*) cultivar Pioneer were used for the experimental study. The initial moisture content (m.c.) of the sample was determined by drying 10 g of unground grain, in triplicate at $130 \pm 2^{\circ}$C for 16 h for rye, 22 h for oats and 3 h for sunflower seeds (ASABE 2006) in a hot air oven (Thelco Laboratory Oven, Winchester, VA) and was expressed on a wet mass basis. The rye and oats were then conditioned to 14, 16, and 18% m.c. and sunflower seeds were conditioned to 8, 10, and 12% m.c. by adding a calculated quantity of distilled water and rotating the grain mixture for about an hour. The samples were then kept in polythene bags and stored in a refrigerator (4°C) for 72 h for uniform moisture distribution. Samples were mixed within the bag every 4 h during the day to ensure uniform distribution of moisture. The moisture content was then verified by drying 10-g samples, in triplicate, and the moisturized grain was then kept in air-tight plastic bags in a refrigerator (4°C) until used for the experiments.

Pilot- scale industrial microwave system

The experiments were conducted in a continuous, pilot-scale, industrial microwave system operated at 230 VAC, 60 Hz, and 23 A (Model No: P24YKA03, Industrial Microwave Systems, Morrisville, NC). The microwave system shown in Fig. 1 consists of a belt assembly, an applicator, a fan and heater assembly and a control panel. The maximum speed of the conveyor was 3 m/min. At the maximum speed of the conveyor, it takes 28 s for the sample to pass the applicator. The conveyor was set at two speeds, 3 m/min and 1.5 m/min so that samples were exposed to microwave energy for 28 and 56 s, respectively. The power output of the generator was adjustable from

Fig. 1. Layout of the industrial microwave system depicting control panel (1), microwave applicator (2), conveyor (3), thermal camera (4), and data acquisition system (5).

0 to 2000 W. The power levels chosen for the study were 200, 300, 400, and 500 W.

Infrared thermal camera

An uncooled focal planar array type infrared thermal camera with 320×240 pixels was used to take thermal images of the microwave-treated grain (Model: ThermaCAM™ SC500 of FLIR systems, Burlington, ON; Spectral range: 7.5–13.0 μm). The thermal sensitivity of the camera was 0.07°C at 30°C. While taking thermal images, the emissivity of the grain was set as 0.98 for all the experiments.

Experimental procedure

A rectangular microwavable polystyrene box, of dimensions 30 cm × 3 cm × 1 cm, was made to hold a 50-g sample of grain. The experiments were conducted by placing the grain sample in the box. The sample was spread along the sample holder and flattened by hand to avoid unevenness in the sample. The sample holder was then placed on the conveyor and the required power and exposure time were selected on the control panel. The sample was then subjected to microwave heating. As the grain sample came out of the conveyor, a thermal image of the sample was captured using the thermal camera. The sample was then taken out, allowed to cool to room temperature and the weight of the sample was measured to determine the moisture loss. The same procedure was repeated for rye, oats, and sunflower seeds at 200, 300, 400, and 500 W and at two exposure times, 28 and 56 s.

From the thermal image obtained for each sample, the maximum, minimum and average temperatures were extracted using ThermaCAM Researcher 2001 software (FLIR systems, Burlington, ON) and the differences between the maximum and minimum surface temperatures (Δt) of the grain were obtained.

Statistical analysis

The effect of moisture content, power and exposure time on the average surface temperature and Δt (difference between the maximum and minimum temperature) was studied using a factorial design. The significance of the different type of grain was analyzed using ANOVA. The analysis of variance was done at 95% confidence interval ($\alpha < 0.05$) and mean separation was done using Scheffe's test. All the analyses were carried out using GLM procedure in SAS version 9.1 (SAS Institute, Inc. 2002).

RESULTS and DISCUSSION

Effect of power and moisture content on average temperature

The average temperature of one replication is the average of all the pixels in the sample. The average temperature of three replications of each of rye, oats, and sunflower seeds are given in Table 1. The thermal images showing the surface temperature distribution of rye, oats and sunflower seeds are shown in Figs. 2, 3, and 4, respectively, for an exposure time of 56 s at 0, 200, 300 and 400 W. The thermal image with the temperature scale provides an understanding of the temperature ranges attained by the samples at various power levels. The images explain the temperature variation between the control and microwave-heated samples and the variation within the samples.

The average temperatures of 14% m.c. rye at 0, 200, 300, 400, and 500 W for 28 s were 27.6, 49.2, 59.0, 72.1, and 82.5°C, respectively, and the average temperatures of 14% m.c. oats were 27.2, 33.1, 35.5, 46.6, and 51.4°C, respectively. The average temperatures of sunflower seeds at 8% m.c. at 0, 200, 300, 400, and 500 W were 23.3, 30.6, 35.1, 39.2, and 43.6°C, respectively. Analysis of variance and Scheffe's test showed that average temperature was significantly higher at higher power levels and exposure times for rye, oats, and sunflower seeds. The average temperature of oats was significantly higher at 18 and 16% m.c. than at 14% m.c. The average temperature of sunflower seeds was significantly higher at 12% followed by 10 and 8% m.c. The average temperature of rye was significantly higher at 14 and 16% m.c. than at 18% m.c. The phenomenon of decreasing temperature with increasing moisture content was also observed by Manickavasagan et al. (2006a). They studied the microwave heating of wheat, barley and canola and their results have shown that the average temperatures of wheat were 108.8, 103.1, 96.9, and 88.5°C for 12, 15, 18, and 21% moisture content, respectively. At the same conditions, the average surface temperatures for barley were 117.5, 106.6, 104.2, and 90.4°C and for canola were 97.5, 94.7, 94.1, and 86.7°C, for 12, 15, 18 and 21% moisture content, respectively. Similar results were also obtained by Nelson (1976), when alfalfa seeds were treated with radio frequency heating, the final temperature increased with decreasing moisture content.

Comparing rye, oats, and sunflower seeds, the average temperature of rye was significantly higher than that of oats and the average temperature of oats was significantly higher than that of sunflower seeds at all the power levels and exposure times. Different materials behave differently during microwave heating. The ability of material to store and dissipate electrical energy is based on the dielectric properties of the specified food material. Hence, knowledge of the dielectric properties of food material is essential for proper understanding of the heating pattern during microwave heating (Mudgett 1982). The dielectric properties of a material (dielectric constant and dielectric loss factor) determine the behavior of interaction of the material during the microwave heating process (Nelson 1992). The dielectric constant (the ability of material to store charge when used as a dielectric capacitor) for rye, oats, and sunflower seeds is 6.0, 4.9, and 2.0, respectively (the dielectric constant of water is 80.3). The higher dielectric constant for rye shows that rye heats faster than oats and sunflower seeds (Khrone 2007). The average surface temperatures obtained by Manickavasagan et al. (2006a) for 12, 15, 18, and 21% m.c. wheat at 500 W and 56 s were 108.8, 103.1, 96.9, and 88.5°C, respectively, and the average surface temperatures of barley at the same conditions were 117.5, 106.6, 104.2, and 90.4°C, respectively. There was no significant difference in the average temperatures of wheat and barley in most of the

Table 1. Average temperature* ±SE (°C) of different moisture content rye, oats, and sunflower seeds exposed to microwave energy for 28 and 56 s measured using a thermal camera.

Grain	Moisture content (%)	Power (W)									
		0		200		300		400		500	
		Exposure time (s)									
		28	56	28	56	28	56	28	56	28	56
Rye	14	27.6±0.1	27.4±0.2	49.2±4.9	65.1±7.9	59.0±7.9	85.4±10.3	72.1±10.4	101.2±9.5	82.5±9.6	107.2±9.5
	16	26.9±0.2	27.2±0.2	49.2±5.6	66.0±8.3	61.0±7.9	83.7±10.0	72.9±8.2	102.3±9.8	83.9±9.9	107.3±9.8
	18	28.3±0.2	27.8±0.3	47.2±5.0	62.3±6.7	60.3±7.6	80.1±8.8	70.1±7.9	94.4±9.9	79.8±9.8	103.2±9.9
Oats	14	27.2±0.3	27.1±0.2	33.1±1.7	43.0±2.9	35.5±3.5	55.5±4.2	46.6±3.3	57.3±4.6	51.4±3.8	67.2±4.6
	16	27.2±0.3	27.3±0.3	37.7±1.8	43.2±2.7	42.6±2.6	53.3±3.6	49.2±3.0	58.4±4.0	53.1±3.4	68.3±4.0
	18	27.0±0.4	27.1±0.2	37.2±1.5	42.5±2.4	42.9±2.8	52.4±3.8	49.1±3.0	60.9±3.3	54.6±3.2	69.1±3.3
Sunflower	8	23.3±0.3	23.3±0.3	30.6±1.8	35.1±3.0	35.1±3.0	41.1±4.4	39.2±4.1	49.6±6.0	43.6±4.7	57.2±6.0
	10	22.8±0.3	22.8±0.3	30.5±2.1	35.2±2.7	35.7±3.0	44.2±4.2	40.9±3.5	49.9±5.4	45.2±4.3	58.2±5.4
	12	19.2±0.7	22.5±0.3	30.7±1.8	36.4±3.2	37.4±3.3	44.6±4.8	43.0±4.2	53.8±6.5	47.3±5.3	60.2±6.5

*Average of three replications (for every replication average temperature is the mean temperature of all the pixels).

treatments. For canola, the average surface temperatures were 97.5, 94.7, 94.1, and 86.7°C, respectively, and the average temperature of canola was significantly lower than that of wheat and barley.

Effect of power and moisture content on Δt

The Δt is the difference between the hottest and coolest spot in a sample. The Δt at 14% m.c. for 200 W and 28 s exposure time for rye and oats were in the range of 23.4–26.2 and 7.7–10.3°C, respectively. The Δt at 500 W and 28 s exposure time for rye and oats were in the range of 42.5–57.7 and 16.2–20.2°C, respectively. The Δt for sunflower seeds at 8% for 200 W and 28 s exposure time was in the range of 7.3–8.7°C and for 500 W and 28 s exposure time was in the range of 18.9–21.1°C.

The Δt increased as power level and exposure time increased for rye, oats, and sunflower seeds, showing that the temperature difference between hotter and colder spots was higher as power and exposure time increased for both the cereals and oilseed. Similar results were obtained by Manickavasagan et al. (2006a) when wheat, barley, and canola were treated with microwave energy.

There was no significant difference in the Δt for the 14, 16, and 18% m.c rye sample showing that moisture has no significant contribution in the non-uniform temperature distribution in rye. Whereas in oats, the Δt was higher at 18 and 16% m.c. compared with 14% m.c. In sunflower seeds, the Δt was significantly higher at 12% m.c. than at 8 and 10% m.c.

Comparing rye and oats, the Δt was higher at all power levels and exposure times for rye than for oats. This implies that the non-uniform heating or the difference between the maximum and minimum temperature was higher in rye than in oats, and oats has a more uniform temperature distribution compared with rye. Oliveira and Franca (2002), in their study on modeling of microwave heating, stated that temperature distribution in a microwave-heated sample is dependent on the sample size and shape. Manickavasagan et al. (2006a) stated that Δt was lower for canola compared with wheat and barley due to the relatively small and spherical shape of the canola seed.

Maximum and minimum temperatures

The minimum and maximum temperatures of rye, oats, and sunflower seeds at 28 s and 56 s exposure times are shown in Table 2.

The minimum temperatures of 14% m.c. rye at 28 s exposure time and at 0, 200, 300, 400, and 500 W power were 27.2, 35.9, 38.8, 45.9, and 54.3°C, respectively, and the maximum temperatures in the same conditions were 28.1, 65.6, 80.3, 95.4, and 112.0°C, respectively. The minimum temperatures of 14% m.c. oats under the same conditions were 26.7, 27.1, 27.9, 37.5, and 40.1°C, respectively, and the maximum temperatures were 27.8, 37.7, 44.8, 55.2, and 60.3°C, respectively. The minimum temperature of 8% m.c. sunflower seeds at 28 s exposure time and at 0, 200, 300, 400 and 500 W were 22.3, 25.6, 27.7, 28.9, and 30.6°C, respectively and the maximum

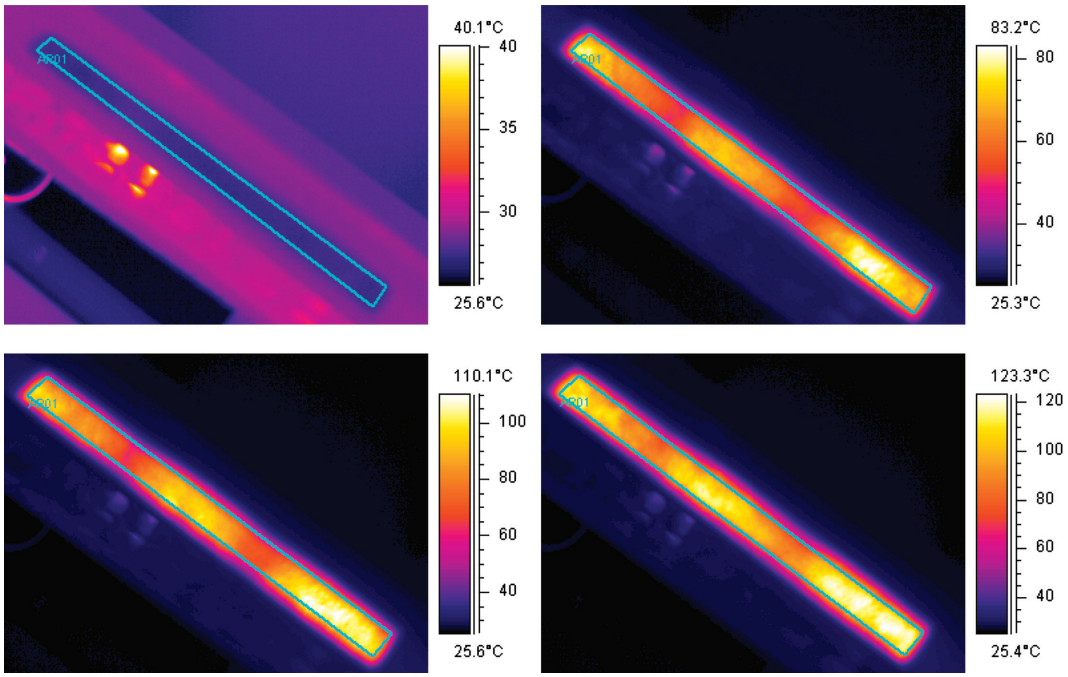

Fig. 2. Thermal images of 14% moisture-content rye at various power levels. (a) Control; (b) 200 W, 56 s; (c) 300 W, 56 s; (d) 400 W, 56 s.

temperatures were 25.3, 34.3, 41.2, 47.6, and 52.8°C, respectively.

The minimum and maximum temperatures of oats were lower than those of rye at the same moisture content, power and exposure time. This shows that when heating rye and oats under similar conditions, the rye heats up faster than the oats. The minimum and maximum temperatures of sunflower seeds were lower than those of oats at all the power levels and exposure times.

Since non-uniform temperature distribution is widely seen in all materials heated with microwave energy, sufficient care must be taken to ensure that minimum temperature is reached and that maximum safe temperature is not exceeded, based on the type of application.

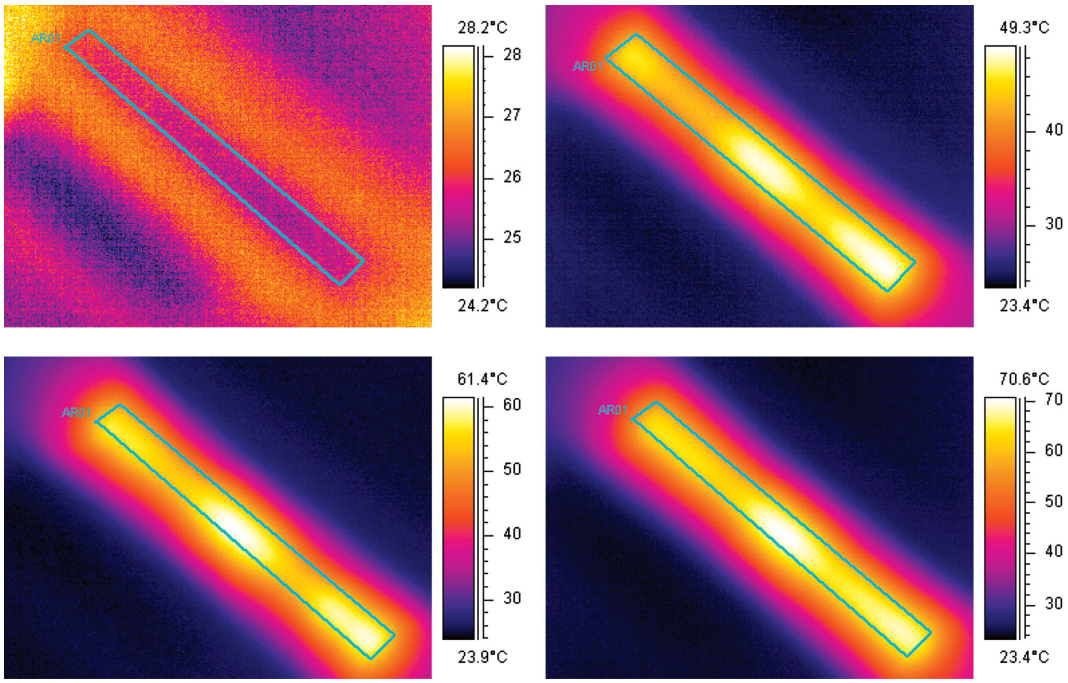

Fig. 3. Thermal images of 14% moisture-content oats at various power levels. (a) Control; (b) 200 W, 56 s; (c) 300 W, 56 s; (d) 400 W, 56 s.

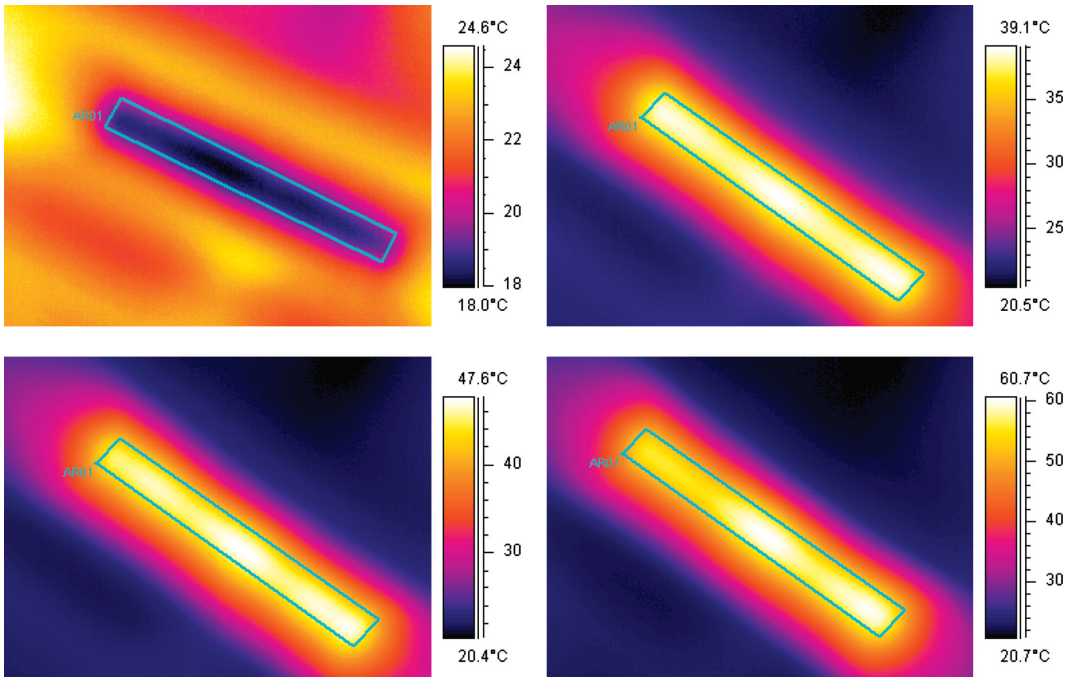

Fig. 4. Thermal images of 8% moisture-content sunflower at various power levels. (a) Control; (b) 200 W, 56 s; (c) 300 W, 56 s; (d) 400 W, 56 s.

For example, when heating meat and related foods, care must be taken to ensure that the minimum temperature required to kill pathogens is attained. The safe recommended temperature during heating of any food material is a minimum of 70°C (Goksoy et al. 1999; Ryynanen et al. 2001). When heating grains using microwaves, care must be taken that the maximum temperature attained at any point is not above the safe temperature (about 60°C), so that the seed is not killed and the end use quality of grain is not affected.

Moisture loss

The moisture loss of rye, oats and sunflower seeds due to microwave heating at 28 s and 56 s exposure times is shown in Table 3.

The moisture loss at 200, 300, 400, and 500 W for 28 s exposure times was 0.8, 1.2, 1.7 and 2.2 percentage points, respectively for 14% m.c. rye. As the exposure time was increased to 56 s, the moisture loss increased to 1.4, 2.5, and 3.9 percentage points for 200, 300, and 400 W, respectively. The moisture loss for 14% m.c. oats at 200, 300, 400, and 500 W were 1.1, 1.6, 2.3, and 3.5 percentage points, respectively. The moisture loss increased to 1.9, 3.2, and 4.5 percentage points as the exposure time was increased. As the power and exposure time were increased, the moisture loss increased in both cereals and oilseed. Analysis of variance shows that m.c, power, and exposure time had significant effects on the moisture loss. The moisture loss was higher at 18% m.c. followed by 16% m.c. and lower at 14% m.c. for both rye and oats. The moisture loss for sunflower seeds was significantly higher at 12% m.c. followed by 10% and was lower at 8% m.c. These results indicate that in both cereals and oilseed the higher the initial moisture content, the higher the moisture loss.

Comparing the moisture loss in both rye and oats, the moisture loss was higher for oats at all power levels and exposure times. This may be because more water is held in the husk of oats, which is lost faster during heating. Possibly because of the higher moisture loss, the temperature of the oats is lower than that of the rye. Higher moisture loss in oats may also be related to the lower Δt in oats than in rye.

CONCLUSIONS

Preliminary studies on microwave heating of rye, oats, and sunflower seeds have shown that a wide range in temperature variation is obtained in microwave-heated samples. Thermal images obtained after microwave heating show regions of hot and cool spots in bulk samples of rye, oats, and sunflower seeds. The average temperature of both the cereals and oilseed increased with an increase in power, exposure time or moisture content, showing a significant effect of all the variables on the average temperature. Comparing rye and oats, the average temperature was higher in rye at all the power levels, exposure times, and moisture contents, indicating that the grains heat differently during microwave heating. Since the maximum temperature attained at certain locations is much higher than the average temperature of any given sample, care must be taken when incorporating microwave heating in the processing of grain, because the grain quality may be affected due to the maximum temperature at certain locations, even though the average temperature would have been in an acceptable range.

Table 2. Minimum and maximum temperatures of rye, oats, and sunflower seeds among the three replicates at different moisture content, power level and exposure time.

Grain	Exposure time (s)	Power (W)	Minimum temperature (°C) at			Maximum temperature (°C) at		
			14% m.c.	16% m.c.	18% m.c.	14% m.c.	16% m.c.	18% m.c.
Rye	28	0	27.2±0.1	25.8±0.5	27.5±0.4	28.1±0	28.3±0.3	30.2±0.9
		200	35.9±1.7	35.6±1.9	35.2±0.7	65.6±3.2	63.5±1.2	61.0±0.5
		300	38.8±1.4	42.3±1.6	41.3±1.5	80.3±2.6	82.6±4.0	81.5±1.7
		400	45.9±0.8	48.2±4.3	46.9±2.1	95.4±2.0	95.2±0.2	93.4±2.5
		500	54.3±3.5	57.3±4.1	52.3±1.0	112.0±4.7	108.8±1.4	109.0±3.6
	56	0	27.2±0.1	25.8±0.5	27.5±0.4	28.1±0	28.3±0.3	30.2±0.9
		200	44.0±2.0	45.7±1.1	41.5±2.0	87.7±1.9	86.7±2.4	80.3±2.0
		300	54.5±3.5	55.4±3.9	53.8±2.2	112.0±4.0	108.2±2.4	101.8±0.9
		400	73.1±2.4	74.4±1.3	60.3±4.1	125.2±4.5	123.8±1.3	122.9±3.8
Oats	28	0	26.7±0.2	26.6±0.3	26.5±0.2	27.8±0.3	27.7±0.3	27.4±0.2
		200	27.1±1.2	32.0±0.6	32.5±0.5	37.7±0.5	42.2±0.2	42.2±1.4
		300	27.9±0.6	35.6±0.3	34.9±0.4	44.8±1.1	50.6±1.2	49.5±0.5
		400	37.5±0.7	40.7±0.6	38.2±2.9	55.2±0.7	56.8±1.0	57.6±0.7
		500	40.1±1.4	43.8±0.4	45.0±1.1	60.3±0.9	63.7±2.6	63.0±1.2
	56	0	26.7±0.2	26.6±0.3	26.5±0.2	27.8±0.3	27.7±0.3	27.4±0.2
		200	34.6±0.5	35.8±0.6	34.8±0.9	49.7±0.3	50.5±0.7	49.0±0.7
		300	42.3±3.2	41.9±1.7	42.2±0.8	71.0±6.0	58.7±5.2	62.3±1.8
		400	43.1±2.0	46.3±1.5	51.0±0.4	71.0±4.7	67.7±1.3	68.5±1.1
			8% m.c.	10% m.c.	12% m.c.	8% m.c.	10% m.c.	12% m.c.
Sunflower	28	0	22.3±0.2	22.1±0.1	17.9±0.1	25.3±0.8	24.0±0.1	22.0±0.2
		200	25.6±0.4	25.8±0.1	25.7±0.2	34.3±0.4	35.0±0.6	34.5±0.3
		300	27.7±0.6	28.1±0.4	28.8±0.4	41.2±0.5	42.0±0.9	43.3±0
		400	28.9±0.5	31.3±0.7	32.1±0.5	47.6±1.1	48.5±1.3	51.8±0.4
		500	30.6±1.3	33.6±0.6	34.1±0.6	52.8±0.6	53.9±0.4	57.2±0.3
	56	0	22.6±0.1	21.8±0.2	21.8±0.1	25.3±0.3	24.6±0.2	25.0±0.5
		200	27.9±0.2	28.2±0.3	28.4±0.1	40.6±0.8	40.5±0.8	43.7±0.8
		300	30.3±0.3	32.0±0.7	31.7±0.7	50.3±1.3	51.9±0.1	54.5±0.4
		400	33.8±1.1	35.9±0.2	36.8±0.9	60.8±0.6	60.0±0.4	66.4±0.3

Table 3. Average moisture loss (in percentage points)±standard error of rye, oats, and sunflower seeds heated with microwave energy at different moisture content, power level, and exposure time.

Grain	Moisture content (%)	Exposure time (s)						
		28				56		
		Power (W)						
		200	300	400	500	200	300	400
Rye	14	0.8±0.2	1.2±0.1	1.7±0.1	2.2±0.1	1.4±0.1	2.5±0.1	3.9±0.1
	16	0.9±0	1.3±0	1.9±0	2.5±0.1	1.8±0	2.7±0.1	4.3±0.2
	18	1.0±0	1.6±0.1	2.1±0.1	2.8±0.1	2.0±0	3.1±0	4.6±0.1
Oats	14	1.1±0.1	1.6±0.1	2.3±0.1	3.5±0.1	1.9±0.1	3.2±0.3	4.5±0.3
	16	1.6±0.1	2.4±0	3.1±0.2	3.9±0.1	2.7±0.1	4.2±0.1	6.0±0.1
	18	1.8±0.2	2.6±0.1	3.8±0.1	4.3±0.1	3.7±0.3	5.4±0	7.4±0.3
Sunflower	8	1.2±0.2	1.5±0.0	1.9±0.1	2.3±0.1	1.4±0.1	2.7±0.1	3.6±0.0
	10	1.4±0.1	1.9±0.0	2.5±0.1	2.9±0.1	1.7±0.0	3.0±0.1	3.4±0.1
	12	2.0±0.0	3.0±0.0	3.5±0.0	4.1±0.0	3.0±0.1	4.2±0.1	5.5±0.1

ACKNOWLEDGEMENTS

We thank the Canada Research Chairs program and the Natural Sciences and Engineering Research Council of Canada for providing financial support for this study.

REFERENCES

ASABE. 2006. *ASABE Standard S352.2 Feb2003: Moisture measurement-unground grain and seeds*. St. Joseph, MI: ASABE.

Buffler, C.R. 1993. *Microwave Cooking and Processing*. Glenview, IL: Van Nostrand Reinhold.

Burfoot, D., W.J. Griffin and S.J. James. 1988. Microwave pasteurization of prepared meals. *Journal of Food Engineering* 8: 145–156.

Fakhouri, M.O. and H.S. Ramaswamy. 1993. Temperature uniformity of microwave heated foods as influenced by product type and composition. *Food Research International* 26: 89–95.

Geedipalli, S.S.R., V. Rakesh and A.K. Datta. 2007. Modeling the heating uniformity contributed by a rotating turntable in microwave ovens. *Journal of Food Engineering* 82: 359–368.

Goksoy, E.O., C. James and S.J. James. 1999. Non-uniformity of surface temperatures after microwave heating of poultry meat. *Journal of Microwave Power and Electromagnetic Energy* 34: 149–160.

Gowen, A., N. Abu-Ghannam, J. Frias and J. Oliveira. 2006. Optimisation of dehydration and rehydration properties of cooked chickpeas (*Cicer arietinum* L.) undergoing microwave-hot air combination drying. *Trends in Food Science and Technology* 17: 177–183.

Gunasekaran, S. and H. Yang. 2007. Effect of experimental parameters on temperature distribution during continuous and pulsed microwave heating. *Journal of Food Engineering* 78: 1452–1456.

Krohne. 2007**.** Dielectric Constant of Substances. http://www.krohne-mar.com/Dielectric_Constants.6840.0.html. (2007/09/08).

Lee, D.S., D. Shin and K.L. Yam. 2002. Improvement of temperature uniformity in microwave-reheated rice by optimizing heat/cold cycle. *Food Service Technology* 2: 87–93.

Manickavasagan, A., D.S. Jayas and N.D.G. White. 2006a. Non-uniformity of surface temperatures of grain after microwave treatment in an industrial microwave dryer. *Drying Technology* 24: 1559–1567.

Manickavasagan, A., D.S. Jayas, N.D.G. White and F. Jian. 2006b. Thermal imaging of a stored grain silo to detect a hot spot. *Applied Engineering in Agriculture* 22: 891–897.

Maskan, M. 2000. Microwave/air and microwave finish drying of banana. *Journal of Food Engineering* 44: 71–78.

Mudgett, R.E. 1982. Electrical properties of foods in microwave processing. *Food Technology* 36: 109–115.

Mullin, J. 1995. Microwave processing. In *New Methods of Food Preservation*, ed. G.W. Gould, 112–134. Bishopbriggs, UK: Blackie Academic and Professional.

Mullin, J. and J. Bows. 1993. Temperature measurements during microwave cooking. *Food Additives Contamination* 10: 663–672.

Nelson, S.O. 1976. Use of microwave and lower frequency RF energy for improving alfalfa seed germination. *Journal of Microwave Power* 11: 271–277.

Nelson, S.O. 1992. Microwave dielectric properties of fresh onions. *Transactions of ASABE* 35: 963–966.

Oliveira, M.E.C. and A.S. Franca. 2002. Microwave heating of foodstuffs. *Journal of Food Engineering* 53: 347–359.

Prabhanjan, D.G., H.S. Ramaswamy and G.S.V. Raghavan. 1995. Microwave assisted convective air drying of thin layer carrots. *Journal of Food Engineering* 25: 283–293.

Ryynanen, S. and T. Ohlsson. 1996. Microwave heating uniformity of ready meals as affected by placement, composition, and geometry. *Journal of Food Science* 61: 620–624.

Ryynanen, S., H. Tuorila and L. Hyvonen. 2001. Perceived temperature effects on microwave heated meals and meal components. *Food Service Technology* 1: 141–148.

Sakai, N. and C. Wang. 2004. An analysis of temperature distribution in microwave heating of foods with non-uniform dielectric properties. *Journal of Chemical Engineering of Japan* 37: 858–862.

SAS Institute, Inc. 2002**.** *SAS User's Guide*. Ver. 9.1. Cary, NC: SAS Institute, Inc.

Varith, J., G.M. Hyde., A.L. Baritelle, J.K. Fellman and T. Sattabongkot. 2003. Non-contact bruise detection in apples by thermal imaging. *Innovative Food Science and Emerging Technology* 4: 211–218.