Fraunhofer Institut Verfahrenstechnik und Verpackung

Report

Microwaveability of Steel and Aluminium Food Packaging

for: Alcan Rhenalu, Biesheim, France

APEAL, the Association of European Producers of Steel for Packaging, Brussels, Belgium

Crown Food Europe, Paris, France

FGM, Fördergesellschaft Metallverpackungen, Düsseldorf, Germany

Impress, Deventer, the Netherlands

Novelis Deutschland, Göttingen, Germany

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Content

Summary

Introduction

Fraunhofer Institute for Process Engineering and Packaging performed an experimental study on microwaveability of different rigid food containers made from steel and aluminium. The study was funded by the following organisations:

Alcan Rhenalu, Biesheim, France
APEAL, the Association of European Producers of Steel for Packaging, Brussels, Belgium
Crown Food Europe, Paris, France
FGM, Fördergesellschaft Metallverpackungen, Düsseldorf, Germany
Impress, Deventer, the Netherlands
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The aim of the study was to look into the safety and performance of microwave heating food in rigid steel and aluminium containers.

This study also refers to some of the findings and experiments conducted in the study on "Microwaveability of Aluminium Foil Packages" carried out by Fraunhofer Institute for Process Engineering and Packaging in 2006 on behalf of the European Aluminium Foil Association (EAFA).

Heating experiments were performed with food packed in five metal containers of different dimensions and shape and with four different popular household microwave oven models .The tested metal containers were:

+ a round steel bowl (99 mm diameter x 35 mm height), used with 200 g filling,
+ a round steel bowl (127 mm diameter x 30 mm height), used with 250 g filling,
+ a square steel container (125 mm x 125 mm x 25 mm), used with 300 g filling,
+ a rectangular aluminium container (160 mm x 99 mm x 35 mm), used with 400 g filling,
+ a round steel container (153 mm diameter, 36 mm height), used with 425 g filling.

These containers were chosen because of their large open surface and shallow profile. This is considered as preferable for use in microwave ovens.

Comparison experiments were performed with plastic containers of similar shape and size, filled with the same quantity of test food. The plastic containers were made of C-PET and were specified for microwave heating.

Test fillings in heating experiments were tap water, egg batter, chili con carne and an infant meal (pasta with vegetables and small meat balls in sauce). All the test materials were liquid or semi-liquid and filled the containers completely from wall to wall.

Microwave nominal power ratings of the four ovens were 700 W, 800 W, 900 W and 1000 W. The oven constructions were of the standard household type with glass turntable and with the opening of the microwave wave-guide in the right side wall of the oven cavity. The volumes of the oven cavities were different. Also different were the constructions of the wave-guide that optimise power transfer from the magnetron into the oven cavity.

Only the microwave heating function of the ovens was used in the heating experiments though some ovens were equipped with infrared grill or hot air circulation. In all experiments, oven power setting was 100% and only the heating time was adjusted to achieve the heating goal. No attempts were made to optimise the heating regime beyond this simple scheme.

The performed experiments were:

+ measurement of heating efficiency with containers filled with tap water
+ visualisation of microwave heating patterns with partly solidified egg batter
+ measurement of heating performance and temperature distribution in containers filled with chilli con carne and infant meal by an array of thermocouples immediately after microwave heating.

In addition, the effects of misuse of metal containers in microwave ovens were analysed and the stability of the oven microwave power level during the experimental series was tested.

Test Results

Heating Safety

When the tested metal containers were employed in microwave ovens in standard food heating experiments, their use was safe. During about 1000 microwave heating experiments with metal containers, which also includes a previous study with other metal containers, not a single spark occurred nor a potentially risky situation was observed.

For safe use of metal containers in microwave ovens the following procedures need to be applied:

+ A metal lid of the container must be removed completely prior to microwave heating.
+ As with containers of other materials, only full containers must be put into the microwave oven.
+ Only one metal container must be heated at a time.
+ The metal container should be placed in the centre of the glass turntable. An insulating air gap of at least 2.5 centimetres between metal container and oven walls must be maintained. For ovens without glass turntable, the container must be placed on a ceramic dish.

In experiments focusing on misuse conditions, where a metal to metal contact was enforced, sparks of different strength occurred. The sparks produced marks in the containers and the oven walls. However, no technical defect of an oven was observed. An air gap of 2 mm between container and oven wall seems sufficient to suppress sparks in all tested situations. Heating instructions for consumers should include an ample safety margin and recommend an air gap of at least 2.5 centimetres.

In normal practice, the raised rim of the oven turntables and the additional use of a plastic dome cover to prevent product splattering make it practically impossible to bring the metal containers unintentionally into contact with floor or walls of the oven cavity.

Heating efficiency and heating times

Microwave heating efficiency is lower in metal containers compared to similar sized plastic containers i.e. for the same heating effect in metal containers, a longer heating time is needed. This has been observed in previous studies and can be derived from the basic fact that in the case of metal containers access of microwave energy to the food is only possible from the open surface side while with plastic containers access is possible from all sides. The actually required heating time for food in metal containers depends on oven power rating and power adjustment, container shape and size, food load, and on oven construction.

For some tested metal containers, the time to heat food to serving temperature was twice as long as for the same food portion in an equivalent plastic container. This resulted e.g. in a time of 3.5 minutes to heat a 250 g portion from a temperature of 10°C to an end temperature of 75°C in an oven with 900 W microwave power. For the smallest metal container with a 99 mm diameter, the heating time was about three times as long as for a similar plastic container. With larger metal containers, a better heating efficiency can be achieved and less heating time difference to similar plastic containers is observed.

Heating patterns and temperature distribution

Heating experiments with egg batter as well as experiments with multiple temperature measurements in heated chili con carne and infant meal showed heating patterns with large differences between maximum temperature (hot spot) and minimum temperature (cold spot). These patterns were observed in plastic as well as in metal trays. They could not be avoided or evened-out by moving the container with the turntable, since they are a characteristic of microwave heating. The actual pattern form or temperature distribution depended on container material, container geometry, food, and oven construction.

Generally, there was less temperature variation and better heating uniformity in the tested metal containers than in equivalent plastic containers, if the food was heated to serving temperature of 75°C.

In the case of chili con carne in metal containers, the difference between measured hot spot and cold spot temperatures was between 20°C and 40°C, depending on container geometry and oven type. In similar plastic containers, a temperature difference between 40°C and 60°C was measured. It is evident that the longer heating times needed to warm up food in metal containers help temperature equilibration by internal heat transfer.

The heating pattern in metal containers showed in most instances high temperatures near the centre and low temperatures near the wall and at the bottom edge. In plastic containers, the highest temperatures were in general measured near the walls and in particular at the bottom edge. The centre region of the plastic container remained cooler in most cases.

Stability of oven performance

Long-term use of microwave ovens leads to normal wear and degradation of power output. It has been suggested that operation of microwave ovens with metal containers may lead to increased degradation and shorter magnetron lifetime beyond normal household wear or may even damage the ovens. To observe changes of power output of the used four microwave ovens during the experimental work, the effective microwave power output of the ovens was tested before and after the series of heating experiments.

After more than 400 heating experiments per oven including 250 experiments with metal containers of different size and misuse experiments with empty containers, we did not observe a rapid decrease of oven power or any oven failure.

Conclusions

+ Microwave heating of food in steel and aluminium containers of a wide open form is safe when following the recommended operating instructions.
+ No functional oven damage or unusual degradation of microwave power has been observed.
+ Microwave heating times for food in metal containers are longer than for food in similar plastic containers. The difference decreases for larger containers. Therefore, it is recommended to use shallow metal containers with a large opening surface.
+ Temperature distribution was generally more uniform in the tested metal containers than in the plastic containers.

1 Situation

Steel and aluminium as packaging material for food are widely used in the canning industry. The advent of convenience products like meals in ready to serve packages and the demand to reheat these meals in the microwave oven has motivated the development of new microwaveable metal packages. Steel and aluminium as packaging material may offer advantages in certain food applications because of their rigidity, good printability, and their good accessibility to material recycling. Previous studies also suggest a better heating uniformity in the microwave oven compared to non-metal containers.

Metal packages in microwave ovens however raise the question of safe oven operation, appropriate heating guidelines, proper "microwave-able" design of the metal packages, good heating efficiency and quality, as well as possible misuse. In order to address these questions, an experimental study with microwave heating of food and test materials in four different coated steel containers and in one rigid coated aluminium container was carried out by Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer IVV). Parts of the study were comparison microwave heating experiments with similar shaped plastic containers and an analysis of oven stability over the duration of the study.

The study was funded by the following organisations:

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2 Goals

The goals of the experimental program are:

- to re-assess safety of microwave heating of food in steel and aluminium containers;
- to analyse and judge potential risks by misuse heating conditions;
- to gain data on heating performance in the microwave oven, in particular heating speed and uniformity compared to similar shaped plastic containers;
- to provide recommendations for container design and heating instructions.

The study will help manufacturers of steel and aluminium containers, food producers, as well as consumers judging the viability and safety of these containers for heating food in the kitchen microwave oven.

3 Scope and description of work

In response to several discussions with the contractors, four containers made from coated steel and one container made from rigid coated aluminium have been selected for microwave experiments. Also three different test foods have been chosen. In addition, critical and misuse situations that might occur in using metal containers in the microwave oven have been analysed and identified and are incorporated into the experiments. As an outcome of the preparing discussions, Fraunhofer IVV suggested an experimental plan that is the basis of the performed study.

Food containers

Four coated steel containers and one rigid coated aluminium container were used in microwave heating experiments:

A) Round container, steel, 99 mm ∅ x 35 mm

B) Round container, steel, 127 mm ∅ x 30 mm

C) Square container, steel, 125 mm x 125 mm x 25 mm

D) Rectangular container, rigid aluminium, 160 mm x 99 mm x 35 mm

E) Round container, steel, 153 mm ∅ x 36 mm

Package E is already in use for food heating in the conventional baking oven. To our knowledge, packages A, B, C and D have not yet been used to reheat food.

Similar containers made from C-PET were used for comparison experiments in order

+ to estimate reduction in heating efficiency that results from electric shielding of the containers´ metal walls (experiment with water) and
+ to characterise difference in heating patterns (experiments with batter).

4 Experimental program

Measurement of oven power

An initial measurement of availability of full nominal oven power was performed at the beginning of the experimental program. The test method follows the European Standard EN 60705, a standard with measurement procedures for the characterisation of usability of household microwave ovens. The measurement was repeated after termination of the heating experiments to detect possible changes in oven power.

Measurement of heating efficiency

Heating efficiency was measured by heating experiments with water as test medium. Temperature increase of water filled into the tested containers was measured during a defined microwave exposition. From this measurement, the thermal power that was absorbed by the container filling was calculated and related to the nominal microwave power of the ovens. A low heating efficiency can result from small absorbing food mass and / or shielding of food by the metal container. Low heating efficiency requires longer heating times to achieve similar heating results as in a situation with high heating efficiency.

Measurements of heating efficiency have been performed with all steel and aluminium containers. Comparison measurements have been made with similar plastic containers.

Generation of visible heating patterns with egg batter

Due to wave interference of microwave fields and to strong coupling of electric fields into exposed and protruding parts of food geometry, characteristic heating patterns of high and low temperatures develop in a food container. These patterns can be visualised by heating liquid egg batter filled into the food container. At locations of high heating power, the batter solidifies fast. At locations of low heating power the batter remains liquid for a long time. Removing the liquid part after a heating experiment leaves the solid fraction which gives a visual impression of the heating power distribution inside the food container. Temperatures as well as the mass fraction of the solidified batter have been measured.

Measurements of heating patterns with egg batter have been carried out with all steel and aluminium containers. Also experiments with similar plastic containers have been performed.

Measurement of temperature distributions in food heated to serving temperature

“Chili con carne” as well as the infant meal were filled into the food containers and heated at full microwave power to an end temperature of about 75°C. This temperature gives a convenient serving temperature and is also in accordance with recommendations of the United States Department of Agriculture (USDA) for reheating chilled food.

The necessary heating time was determined in preparation experiments. Temperatures inside containers were measured at 18 to 50 grid points – depending on container size - and recorded with an automatic measurement device. Mean temperature increase and the difference between hot and cold spot were calculated from the temperature measurements. In addition, thermal power and heating efficiency were calculated including thermal effect of evaporation. Comparison experiments were performed in similar shaped plastic containers.

Misuse experiments

Inadequate use of metal containers in microwave ovens may lead to potentially hazardous situation or to damage of ovens. Two relevant situations of inadequate use were identified during preparation of the experimental programme:

a) Metal containers, if placed at the edge of the oven's turntable by the consumer, may come very close to or even touch the oven walls. This may cause electric sparks or flashover between container edge and oven wall. The distance between container edge and oven wall at which sparks or flashover may occur was investigated with empty and water filled containers. The tests included the four larger containers in all four microwave ovens.

b) The consumer may place two metal containers very close to each other on the turntable of the microwave oven. Flash-over between the two containers may result from this unfavourable arrangement. Tests were performed with the smallest container, empty as well as water filled.

All experiments were repeated a minimum of three times. In many cases significantly more repetitions were carried out in order to tune parameters to achieve the desired heating effect or to repeat experiments with parameter or temperature measurement errors.

5 Materials and methods

5.1 Food containers used in the study

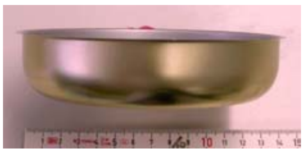
Four different steel containers and one rigid aluminium container were provided by metal packaging manufacturers. Similar shaped C-PET containers were searched on the market and purchased by Fraunhofer IVV for comparison experiments. All containers have a shallow profile and a large open-surface / volume ratio. It is known from previous studies and from physical considerations, that a large open surface and a low filling height are favourable for good heating performance in microwave ovens. The C-PET containers are specified for microwave use.

The very sharp edges of four metal containers, obtained in the course of the can manufacturing process, are rounded during the industrial filling and closing operation. The resulting rounded edge geometry is less prone to spark forming. And with this rounded edge geometry, consumers buy and re-heat metal food containers.

These four metal containers were provided in both versions: with sharp and with rounded edges. Anticipating that the edge geometry does not influence heating performance, most of the food heating experiments were performed with the sharp edge form. Spark forming and flashover tests were performed only with the rounded edge form of seamed containers that had been closed and re-opened.

Table 5.1 contains photographs and additional data of the used metal containers, table 5.2 shows photographs and additional data of the used C-PET containers.

Table 5.1: Steel and aluminium containers used in the study

  	**Denomination: ∅ 99** Round steel (tin plate) container ∅ 99 mm x 35 mm. Used with 200 g model food filling in heating experiments. Heating experiments were performed with the un-seamed, sharp-edge version of the container. Experiments on misuse were performed with the seamed and round edge version after closing and reopening the container.
  	**Denomination: ∅ 127** Round steel (tin plate) container ∅ 127 mm x 30 mm. Used with 250 g model food filling in all heating experiments. Heating experiments were performed with the un-seamed, sharp-edge version of the container. Experiments on misuse were performed with the seamed and round edge version after closing and reopening the container.

	**Denomination: ☐ 125** Square steel (tin plate) container 125 mm x 125 mm x 25 mm. Used with 300 g model food filling in all heating experiments.
	**Denomination: ☐ 160x99** Rectangular rigid aluminium container 160 mm x 99 mm x 35 mm. Used with 400 g model food filling in all heating experiments. Heating experiments were performed with the un-seamed, sharp-edge version of the container. Experiments on misuse were performed with the seamed and round edge version after closing and reopening the container.
	**Denomination: ∅ 153** Round steel (tin plate) container, ∅ 153 mm x 36 mm. Used with 425 g model food filling in all heating experiments. Heating experiments were performed with the un-seamed, sharp-edge version of the container. Experiments on misuse were performed with the seamed and round edge version after closing and reopening the container.

Table 5.2: C-PET containers used for comparison microwave heating experiments

	**Denomination: ∅ 99*** Round C-PET container, ∅ 102 mm x 39 mm. Used with 200 g model food filling in all heating experiments.
	**Denomination: ∅ 127*** Round C-PET container, ∅ 119 mm (interior top) x 28 mm. Used with 250 ml model food filling in all heating experiments.
	**Denomination: □ 125*** Square C-PET container, „hand crafted“ from a rectangular container, 130 mm x 130 mm x 40 mm. Used with 300 g model food filling in all heating experiments.
	**Denomination: ▯ 160x99*** Rectangular C-PET container, 155 mm x 110 mm x 35 mm. Used with 400 g model food filling in all heating experiments.
	**Denomination: ∅ 153*** Round C-PET container, ∅ 140 mm x 35 mm. Used with 425 g model food filling in all heating experiments. The “ears” have no practical influence on the microwave field inside the food filling

5.2 Model foods

The heating experiments were performed with different model foods and media, which were taken in parts from European Standard EN 60705 for household microwave ovens (STANDARD 1999).

I) The medium tap water at the institute has an electric conductivity of 0.7 mS/cm at room temperature. The low viscosity liquid makes it possible to stir and to measure a true mixing temperature after heating instead of a temperature distribution. In addition, the thermal capacity of the medium is exactly known. Therefore the medium is useful to measure absorbed microwave power in tests of oven power and in experiments on microwave heating efficiency in different food containers.

II) A semi-liquid medium used with trays was an egg batter according to EN 60705, Appendix A. The recipe is:

200 g	wheat flour
70 g	whole egg
20 g	sugar
4 g	salt
165 g	water

The liquid batter solidifies during heating. If heating is stopped after a partial solidification, heating patterns can be made visible by separation of liquid from solidified parts. The egg batter was used to visualise heating patterns in the five metal containers and to compare to heating patterns in similar shaped plastic trays.

III) A further model was a ready meal: “Chili con carne”, ERASCO Gastro line, in a 5 kg can. The food is semi-liquid with particles. It is rather salty and has a high electric conductivity. The high viscosity of the food suppresses convection. Therefore temperature patterns which are generated by the microwave field are preserved during heating and temperature distribution measurement.

IV) The last model was a ready infant meal: “Vegetable with egg pasta and small turkey meat balls“, BEBIVITA “Kinderteller” in glass jar. It is again a semi-liquid food with particles but with lower salt content and lower electric conductivity compared to ”Chili con carne” (Model food III).

5.3 Used microwave ovens

Four different popular microwave ovens were used in the study. Their main characteristics as stated in the data sheets are summarised in table 5.3. The ovens have been purchased in different electric appliance stores in the Munich area during mid 2005. All four ovens follow the same basic design: the microwave energy enters into the oven cavity through an opening (a wave-guide) at the right side wall of the cooking chamber. However, the mounting of the magnetron and the polarisation of the microwave field entering the cooking chamber can be different. Two ovens with vertical arrangement of the magnetron antenna and two ovens with horizontal arrangement of antenna are in the selection. Also, all ovens are equipped with a glass turntable. Specific characteristics, in particular the design of the wave-guide in the used ovens, are shown in Appendix B.

Other oven designs are available but are sold in smaller numbers and were not considered in the study. These ovens are combined microwave/baking ovens for kitchen integration or larger ovens for food-service.

Table 5.3: Microwave ovens used throughout the heating experiments.

Manufacturer	Panasonic	Sharp	Sharp	Medion
Model	NN-A764 (Inverter oven)	R-734	R-208	Micromaxx MM 41580
Cooking chamber size (W/H/D) in mm	359/217/353	342/207/368	322/187/336	288/205/287
Volume of cooking chamber in l	27	26	20	17
Diameter of turntable in mm	340	325	272	245
Microwave power in W (data sheet)	1000	900	800	700
Power consumption in W (data sheet) without additional heating modes	1250	1370	1180	1150
Short name in report	Panasonic	Sharp 1	Sharp 2	Micromaxx

All ovens were measured for microwave power output at the beginning of the experimental work and were found to be in the same good condition as after purchase. Detailed results of oven power measurement are given in section 6.4.

For the heating experiments, all ovens were used with their glass turntables. Metal cookware or browning dishes that were part of some of the oven accessories were not used. Trays and other food containers were placed in the centre of the turntable. Microwave power was always set to maximum position in all heating experiments.

5.4 Procedures, measurements and evaluation

Measurement of oven power

The actual microwave heating power of ovens can be measured according to European Standard EN 60705, section 8, with a standard water load of 1 litre. [STANDARD 1999]. In this set-up, the microwave power is nearly completely converted into thermal power in the water.

One litre of tap water of 10°C is filled into a container, e.g. a large beaker of laboratory glass (figure 5.1). The oven is set to maximum power and switched on until the water temperature reaches about 20°C. Heating time and average temperature increase are measured. From temperature increase, heating time, heat capacity of water and fractional heat capacity of glass container, the thermal power of the oven can be calculated.

The heating experiments were repeated several times to obtain improved validity and accuracy of measurement.

Figure 5.1: Arrangement of 1 litre tap water in a glass container for measurement of actual oven power

Measurement of microwave heating efficiency in food containers

To measure the heating efficiency of food in metal and in plastic containers, microwave heating experiments with tap water were carried out. The tested containers were filled with the quantities of tap water as indicated in tables 5.1 and 5.2. Water temperature at start of heating was near 10°C. The ovens were operated at full power. Heating times were varied from 35 s to 61 s to compensate for the different nominal oven powers, the different water quantities in the containers, and the container material. During the applied short heating times, the water temperature raised only by a small margin above room temperature. In this way, heat exchange between water and surrounding by convection and evaporation could be kept low and energy calculations were easier and more accurate. After the end of heating, the water in the trays was stirred to achieve a true mixing temperature and to average the complex microwave heating patterns. Taking into account the heat capacity of the water and the temperature increase during heating, the heating power can be calculated. The calculated heating power divided by nominal oven power provides a simple and straightforward measure for comparison of heating efficiency with different tray materials and geometries.

Measurements of heating efficiency were carried out with all metal and plastic containers in all four ovens. At least four repetitions were made for each container / oven combination.

Misuse experiments with metal containers

Empty as well as water filled metal containers were placed inside the four microwave ovens in order to provoke sparks. Containers were moved beyond the rim of the glass turntable to bring them into direct contact with the oven wall. The small ∅ **99** containers were placed in pairs with direct contact between containers centred on the turntable. In a second series, an air gap of about 1 mm between container and oven wall or between two small containers was adjusted. Frequency and intensity of spark forming were observed in several repetitions of an experimental setting.

Heating experiments with egg batter

Heating experiments with egg batter are suggested in standard EN 60705, Appendix A [STANDARD 1999] to characterise heating patterns. The liquid batter starts to solidify, if heated above a temperature of 70°C to 80°C. If the heating time is chosen to achieve a partial solidification, a pattern of solidified batter is obtained, which provides information on temperature distribution by the non-uniform microwave heating.

1 filling the required amount of fresh egg batter into the container;
2 measurement of start temperature (should be around 10°C);
3 MW-heating, time chosen for about 50% solidification;
4 separation of liquid and solid fraction;
5 photographic documentation of pattern
6 weighing of solid fraction.

Steps 1 and 2, 4

Figure 5.2: Procedure steps for heating experiments with egg batter

The experimental procedure consists of the following steps, which are also visualised in figure 5.2:

Experiments with egg batter were carried out with all metal and plastic containers in all four ovens. Single heating experiments were repeated at least four times to better recognise regularities of formed patterns. Additional experiments were needed to adjust heating times and to verify complete solidification of egg batter in metal containers.

Measurement of temperature distributions

In heating experiments with “chili con carne” and infant meal, temperature distributions were measured in all tested metal containers as well as in similar plastic containers for comparison. The measurement was carried out with arrangements of 9 to 25 thermocouples mounted on a holder (figure 5.3). The patterns of the thermocouple arrangements were adapted to the shapes of the used containers (table 5.5). Therefore five different holders were produced in the workshop of the Institute. The holders were mounted to an automatic positioning device that moved the tips of the thermocouples to two measurement positions inside the containers (figure 5.4). 18 to 50 temperature readings – depending on the container size - were recorded with a multi-channel measurement device.

The sequence of the experiment consisted of the following steps:

1 weighing in the required amount of sample food into the container;
2 measurement of start temperature (should be around 10°C);
3 MW-heating; time chosen to achieve an average end temperature of 75°C;
4 measurement of temperature distribution;
5 weighing for determination of evaporation loss.

Temperature distribution measurements were taken with all container / oven combinations. At least four repetitions were made. Additional repetitions were necessary to tune heating parameters and to correct faulty measurements.

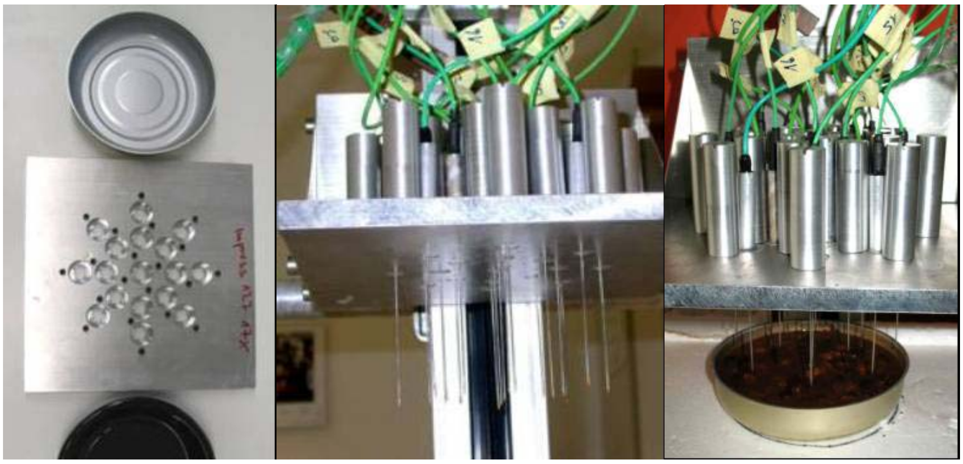


Figure 5.3: Measurement set-up for temperature distribution measurement. From left: Thermocouple holder adapted to container shape; holder equipped with thermocouples in injection needles and mounted to an automatic positioning system; measurement system in action.

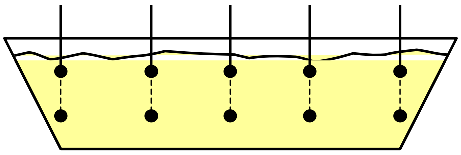


Figure 5.4: Scheme of measurement points inside a container with two measurement levels.

This form of temperature distribution measurement involves some shortcomings, but it is a large improvement compared to a manual measurement with a single thermocouple. The shortcomings are:

a) A limited local resolution by using a limited number of thermocouples and only two measurement planes.

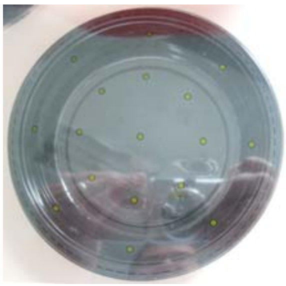
b) The inaccuracy in positioning the thermocouple array results in uncertainty with respect to the real position of the measurement points.

b) The inability to include the most exterior parts of the food filling into the measurements. Some distance of measurement points from container walls and container bottom must be kept in order to avoid collisions between the mechanical sensitive thermocouples and the container material. Also the upper measurement plane must have some distance from the surface of food filling in order to make sure, that all thermocouples have penetrated the sometimes irregular surface and can deliver a valid measurement.
Therefore, the real maximum and minimum temperatures may have been missed by the temperature distribution measurement because they were located between measurement points or outside the measured area.

Still, the temperature distribution measurements though subject to limitations and errors provide valuable information on the real temperature distribution and allow some conclusions on heating patterns, average temperature increase and heating uniformity. In particular, they allow comparisons between heating performance of metal and plastic containers, between different container shapes and sizes, and between different oven models.

Since the temperature distribution measurements and the values derived from it play a crucial role in the presentation of experimental results on heating efficiency, heating times, heating patterns and heating uniformity, the derived values are discussed in some detail in the following lines.

Table 5.5: Temperature measurement patterns in used metal and plastic containers.

	**∅ 99** 2 x 9 = 18 temperature measurement points		**∅ 99*** 2 x 9 = 18 temperature measurement points
	**∅ 127** 2 x 17 = 34 temperature measurement points		**∅ 127*** 2 x 17 = 34 temperature measurement points
	**□ 125** 2 x 25 = 50 temperature measurement points		**□ 125*** 2 x 25 = 50 temperature measurement points
	**□ 160x99** 2 x 25 = 50 temperature measurement points		**□ 160x99*** 2 x 25 = 50 temperature measurement points
	**∅ 153** 2 x 17 = 34 temperature measurement points		**∅ 153*** 2 x 17 = 34 temperature measurement points

Evaluation of temperature distribution measurements

Figure 5.5 shows a typical temperature distribution measurement in a ∅ **127** container arranged in an Excel-sheet roughly similar to the arrangement of measurement points. From the large numbers of single temperature measurements, several condensed values are derived by calculation:

measurement position above container bottom:

13 mm

		81		
	78,1	66,4	71,6	
	66,5		77,7	
84	74,6	67	82,6	80,9
	84,7		80,4	
	84,2	64,3	78,2	
		66,8		

8 mm

		74,2		
	89,9	55,4	83,9	
	65,2		67,5	
92,6	81,7	62,4	88,1	82,4
	80,5		85,8	
	89,8	62,9	82,4	
		67,2		

Figure 5.5: Results of a temperature distribution measurement in a ∅ **127** *metal container filled with infant meal after 200 s heating in the Sharp I oven. Two measurement positions in 13 mm and in 8 mm height above support of measurement set-up were carried out.*

<u>Mean end temperature after heating</u>

First attempts to measure average end temperature by producing a true mixing temperature with stirring of the food filling, similar to experiments with water heating, failed. Uniformly mixing the viscous food with large particulates (beans, meat pieces, pasta pieces) was difficult and the high end temperature resulted in considerable evaporation losses.

Therefore, the decision was taken to use the temperature distribution measurement as sole information for temperature increase and to calculate the arithmetic mean of all temperature values in a temperature distribution measurement as the representative number for the average end temperature of the food portion.

The errors and difficulties of concluding from the measured temperature distribution to the real temperature distribution, as discussed above, apply here similarly. In addition, measurement points do not represent equal food volumes; therefore, the arithmetic mean is subject to inaccuracy. However, similar considerations apply to different schemes of calculating a weighted average. The arithmetic mean seems a pragmatic and simple approach, not worse or more error prone than other, more complicated approaches.

The calculated mean end temperature was then used as basis for adjusting the heating time, and for calculation of heating efficiency or rather "specific heating time".

Specific heating time

In order to compare heating performance of different containers and different oven models on equal footing, we introduce the value of "specific heating time". The "specific heating time" is derived from the actual experimental heating time. The actual heating time results from tuning experiments where the heating time of a specific container with food filling in a specific oven is adjusted until the average end temperature as calculated from temperature distribution measurement is near the required value of 75°C. The specific heating time is obtained by first correcting the actual heating time for small variations of the average temperature increase from the desired increase of 75°C-10°C=65°C. Then, the corrected heating time is divided by the mass of the container food filling and finally multiplied with the relation of nominal oven power to 1000 W.

The resulting "specific heating time" is the time that is needed to heat 1 gram of the food by 65°C in an oven with 1000 W microwave power and is given in seconds per gram or s per g. The influence of different portion sizes and nominal oven powers is compensated in this derived value. The value is inverse proportional to heating efficiency but provides a more pictorial description of heating performance.

In the case of heating experiments with water, a "specific heating time" was calculated directly from measurements of heating efficiency.

Maximum temperature difference in food portion

The maximum temperature and the minimum temperature in a measured temperature distribution are taken to calculate the maximum temperature difference within one food portion. This value is used as a measure of heating uniformity. The larger the calculated maximum temperature difference, the more non-uniform is the heating.

Again, the limitations and errors of the used temperature distribution measurement method affect the validity of the obtained value and were discussed above.

Heating pattern

Finally, a procedure is applied to lower arbitrary variations in temperature distribution measurements and to extract more clearly the basic heating pattern. To this goal, temperature distribution measurements of 4 to 8 experimental repetitions of the same container / oven combination are summed up point by point. The resulting array of sums is divided by the sums of average end temperatures. In the end, an array of percent values is obtained where a value of 100% indicates average end temperature (75°C), a value smaller than 100% indicates a temperature below average, and a value larger than 100% stands for an end temperature above average. Figure 5.6 shows a heating pattern obtained by this numerical procedure. Positions with large deviations below (cold spot) or above (hot spot) the average end temperature are indicated by colouring: red – hot spot, blue – cold spot.

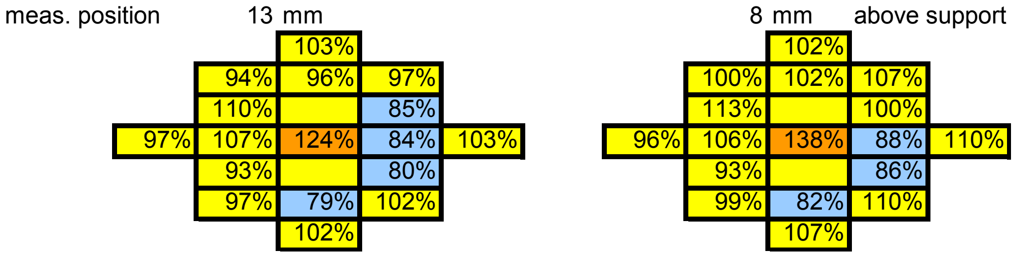


Figure 5.6: Heating patterns extracted from temperature distribution measurements. (Red: hot spot; blue: cold spot; yellow: intermediate temperature.)

6 Experimental results

6.1 Heating safety

If direct contact between metal containers and oven wall was enforced by moving the metal containers over the edge of the turntable or by putting two small containers side by side in direct contact on to the turntable, in nearly all cases strong sparks were produced (see tables 6.1 and 6.2). Ovens were adjusted to full power in all misuse experiments.

Sparks were particularly strong, if containers were empty (figure 6.1), i.e. if the oven was operated without absorbing load and if the contact took place near the wave-guide window in the right side wall of the oven cavity. Both factors provide for very high electric field intensities at the location of contact and support sparking.

The marks in the containers and on oven walls were visually impressive (see figures 6.1 to 6.3). The aluminium container even showed a small hole after strong sparks (figure 6.3). After wiping with a cloth, only small marks and imprints remained on the oven walls that could easily be covered with a white lacquer. No oven damage or influence on technical functionality of the ovens was observed.

In a second series of experiments, a small air gap of about 1 mm between edge of metal containers and walls of oven cavity was adjusted. With empty containers in three situations a spark was observed. Only the larger containers were affected and only the ovens Sharp II and Micromaxx. After filling the containers with tap water, only in one situation, the □**160x99** aluminium container in the Sharp II oven, a spark was observed.

We conclude that a gap of 2 mm and a filling of containers with food would be sufficient to safely suppress sparks between metal containers and oven wall. If the containers are placed centred on the glass turntable and if only a single container is put there, then sparks seem to be impossible. Heating instructions for consumers should include an ample safety margin and should recommend at least 2.5 centimetres air gap.

The concave edge of the glass turntable prohibits an unintended slipping of containers to the oven wall. In order to provoke sparks, we used a PTFE support as seen on the right side of figure 6.1 that helped to shift the container beyond the turntable edge. If additionally a plastic cover in dome shape (a splatter shield) is used, then an unintended contact between metal container and oven wall is not possible.

Figure 6.1: Empty ∅ **127** *container touching the oven wall in Micromaxx oven.*
Marks visible on container and on oven wall after several very strong sparks resulting from a number of repetitions of the experiment.

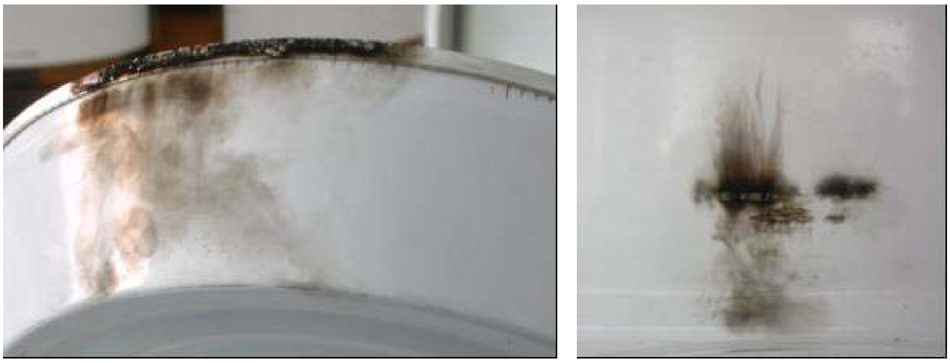


Figure 6.2: Empty ∅ **153** *container touching the oven wall in Micromaxx oven.*
Marks in container and on oven wall after a very strong spark. Marks on oven wall result from several experiments.

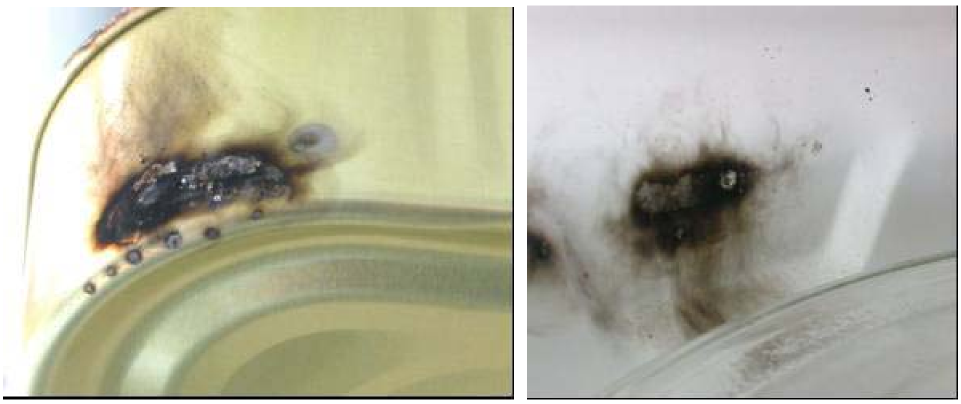


Figure 6.3: Empty □**160x99** *aluminium container touching the oven wall in Micromaxx oven.*
Marks in container and on oven wall after a very strong spark.
Marks on oven wall result from several forced misuse experiments.

*Table 6.1: Results of experiments with direct and enforced contact between metal container and oven wall or between two containers (∅ **99**).
Containers were empty.*

Container without filling	Oven			
	Panasonic	Sharp I	Sharp II	Micromaxx
∅ 99	strong sparks	strong sparks	strong sparks	strong sparks
∅ 127	no spark	strong sparks	strong sparks	strong sparks
☐ 125	strong sparks	sparks	very strong sparks	very strong sparks
∅ 153	sparks	sparks	strong sparks	very strong sparks
▯ 160x99	sparks	sparks	very strong sparks	very strong sparks

*Table 6.2: Results of experiments with direct and enforced contact between metal container and oven wall or between two containers (∅ **99**).
Containers were filled with tap water.*

Container filled with tap water	Oven			
	Panasonic	Sharp I	Sharp II	Micromaxx
∅ 99	strong sparks	sparks	strong sparks	sparks
∅ 127	no spark	sparks	no spark	sparks
☐ 125	strong sparks	sparks	no spark	strong sparks
∅ 153	sparks	strong sparks	sparks	strong sparks
▯ 160x99	no spark	sparks	very strong sparks	very strong sparks

*Table 6.3: Results of experiments with 1 mm gap between metal container and oven wall or between two containers (∅ **99**). Containers were empty.*

Container without filling	Oven			
	Panasonic	Sharp I	Sharp II	Micromaxx
∅ 99	no spark	no spark	no spark	no spark
∅ 127	no spark	no spark	no spark	no spark
☐ 125	no spark	no spark	no spark	sparks
∅ 153	no spark	no spark	sparks	no spark
▯ 160x99	no spark	no spark	no spark	sparks

Table 6.4: Results of experiments with 1 mm gap between metal container and oven wall or between two containers (∅ **99***). Containers were filled with a standard load of tap water.*

Container filled with tap water	Oven			
	Panasonic	Sharp I	Sharp II	Micromaxx
∅ 99	no spark	no spark	no spark	no spark
∅ 127	no spark	no spark	no spark	no spark
□ 125	no spark	no spark	no spark	no spark
∅ 153	no spark	no spark	no spark	no spark
▯ 160x99	no spark	no spark	sparks	no spark

Clearly, an empty metal container touching the oven wall is a critical situation and must be avoided in any case. Most certainly, a strong spark will be produced and will leave marks on container and oven wall. Despite the sometimes spectacular visual effects, there was no safety threat to persons standing near the oven.

In most standard kitchen ovens equipped with glass turntables, this critical situation is unlikely to occur. The raised rim of the turntables and the additional use of a plastic dome cover to prevent splatter make it practically impossible to bring the metal containers unintentionally into contact with floor or walls of the oven cavity.

The situation is completely safe, if the metal containers are filled with food and stand centred on the glass turntable. In standard operation of the microwave ovens and with normal handling of the tested metal containers, their use for microwave heating is safe. During about 1000 microwave heating experiments with metal containers, which include a previous study with other metal containers, not a single occurrence of a spark or any other potentially risky situation was observed.

For safe use of metal containers in microwave ovens the following procedures need to be applied:

+ A metal lid of the container **must** be removed completely prior to microwave heating.

+ As with containers of other materials, only full containers must be put into the microwave oven.

+ Only one metal container must be heated at a time.

+ The metal container should be placed in the centre of the glass turntable. An insulating air gap of at least 2.5 centimetres between metal container and oven walls must be maintained. For ovens without glass turntable, the container must be placed on a ceramic dish.

If these rules are applied, we see no reason from a safety point of view, to exclude wide open and shallow metal containers from use in microwave ovens. Even in the case of misuse, like in the experiments described above, no safety threat will result for the oven operator. The ovens were not affected or damaged in our experiments, apart from marks in the lacquer of oven walls, which may be considered as an aesthetic issue but not as a technical defect.

6.2 Heating efficiency and heating times

Microwave heating efficiency is lower in metal containers compared to similar sized plastic containers, i.e. for the same heating effect in metal containers, a longer heating time is needed. This has been observed in previous studies [PFEIFFER 2006-a, AHVENAINEN 1992, RISMAN 1992, ALUSUISSE 1987, DECAREAU 1978] and can be derived from the basic fact that in the case of metal containers access of microwave energy to the food is only possible from the open surface side while with plastic containers access is possible from all sides.

Three series of heating experiments were performed in order to quantify the microwave heating times needed to achieve similar heating effects in metal as in plastic containers. A first series applied tap water as model “food” since it can be stirred easily after heating to achieve and measure a real mixing temperature and to calculate the average temperature increase or heating power. The heating efficiency was calculated by dividing the calculated heating power by the nominal oven power. In the experiments with tap water, heating times were short and temperature increase was low in order to suppress heat loss to the surrounding.

A second and a third series of experiments used “chili con carne” and an infant meal as fillings for the containers. The heating effect was quantified by measuring temperatures at 18 to 50 measurement points in the filling and calculating the arithmetic mean of these point measurements. The experiments with real food tried to achieve an average temperature increase from a chilled storage temperature of 10°C to a serving temperature of 75°C. Heating times were adjusted accordingly in preparation experiments.

In order to compare results between ovens of different power rating and between containers of different size and filling quantity, the calculated value “specific heating time” is introduced. This is the time to heat 1 gram filling from 10°C to 75°C in a 1000 W oven. It is obtained from the real heating time in the experiment by dividing by mass of filling and normalising oven power to 1000 W.

The following diagrams show the measurement values against surface area of the containers. It is estimated, that the size of open surface area of metal containers through which the microwave energy can reach the food is an important parameter in heating efficiency. Trials to present the experimental results against container diameter or diagonal gave less appealing visual results. The kind of presentation does not imply that the open surface area is the only or most significant factor on heating efficiency. Container shape and the oven construction play also an important role.

Heating Experiments with Tap Water Filling

Figures 6.4 to 6.6. show results of heating experiments with tap water. In figure 6.4, the calculated heating efficiency is displayed. As expected, heating efficiency is lower with metal containers than with similar plastic containers. Efficiency values cover the range from 35% to 48% in the case of the tested metal containers and between 72% and 83% in the case of similar plastic containers. The efficiency is better with larger containers. The relation of heating efficiency between water in plastic containers and in metal containers is between 1.5 for the larger containers in some ovens and more than 2 for containers in the Panasonic oven.

In the case of metal containers, a large variance of heating efficiency for a specific container in different ovens can be seen. The Panasonic oven usually shows a lower efficiency with metal containers than the other ovens while the Sharp I oven performs rather well. Obviously, the different oven constructions influence heating efficiency of water in metal containers much more than they do with plastic containers.

The results of later experiments using real food in metal containers will show that the large variation of efficiency and specific heating time are not observed to the extent as with water filling.

In figure 6.5, the experimental results of figure 6.4 are transformed into specific heating times for heating 1 gram water from 10°C to 75°C in a 1000 W oven. These values are calculated from heating efficiencies and extrapolate heating behaviour from the small real temperature increase in water heating experiments of about 10°C to the full temperature increase of 65°C used in experiments with food.

The information contained in the diagram is essentially the same as in figure 6.4, only the arrangement is reversed since heating time and heating efficiency are inverse to each other. The values of specific heating times are between 0.6 seconds per gram for the larger metal containers and 0.92 seconds per gram for a small metal container. The values for plastic containers range from 0.35 seconds per gram to 0.39 seconds per gram. Again, the large variation of heating time for the same metal container in different ovens is very noticeable.

In figure 6.6, experimental results of an earlier study with different metal containers and water filling are included. The added measurement points support the observation, that larger containers show a better heating efficiency or a smaller specific heating time. It may also be derived that the variation of specific heating time of the same container in different ovens is smaller for the two large containers □ **222x173** and □ **185x134**.

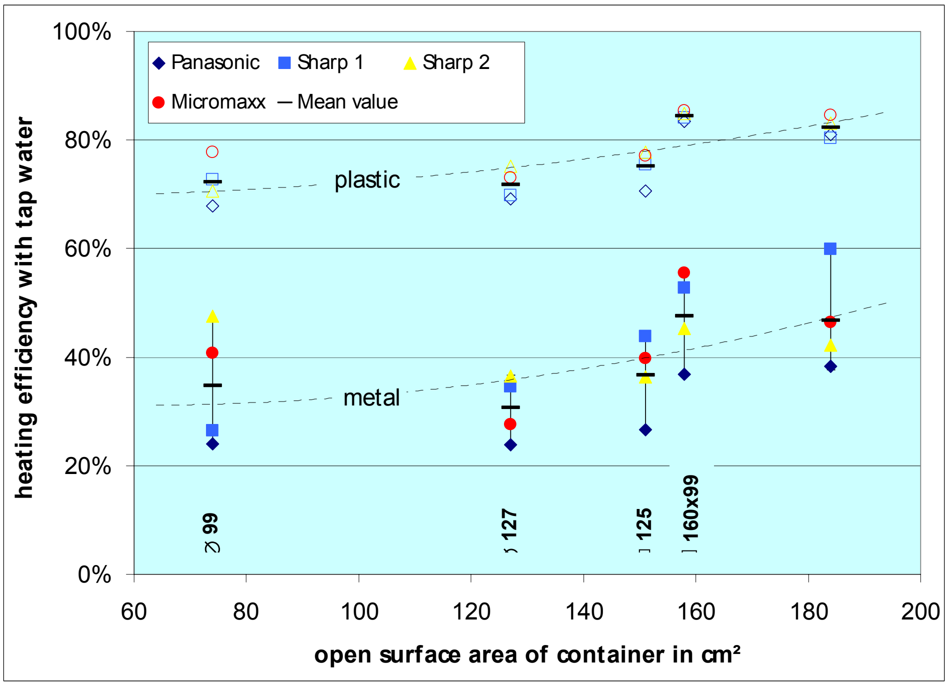


Figure 6.4: Results on microwave heating efficiency with tap water.
Results for metal containers and similar plastic containers are displayed

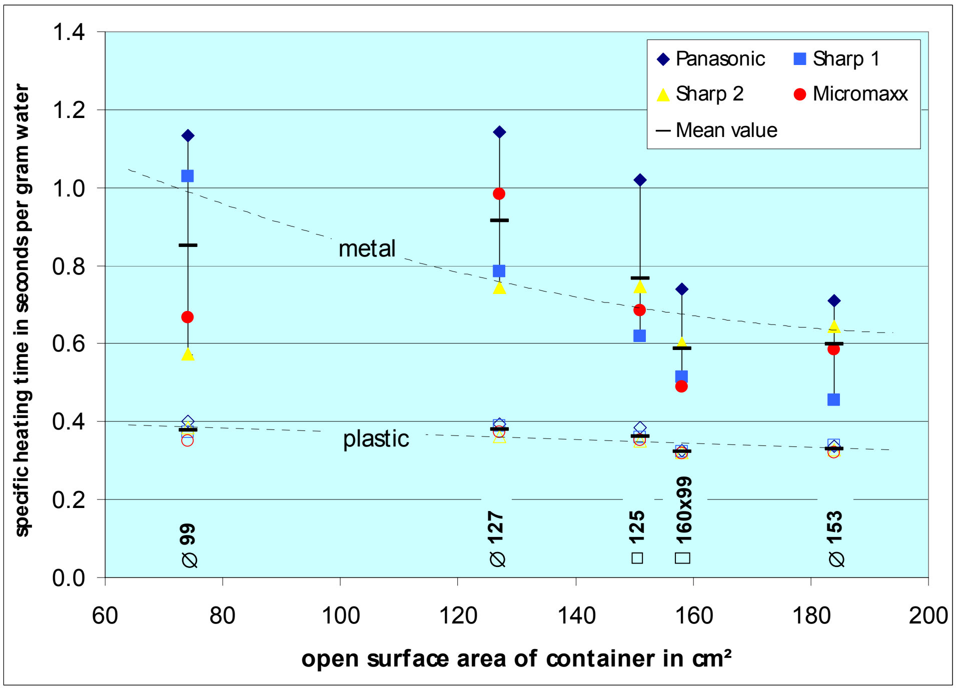


Figure 6.5: Results on specific heating time in seconds per gram tap water normalised for a 1000 W oven. Metal and plastic container results are displayed.

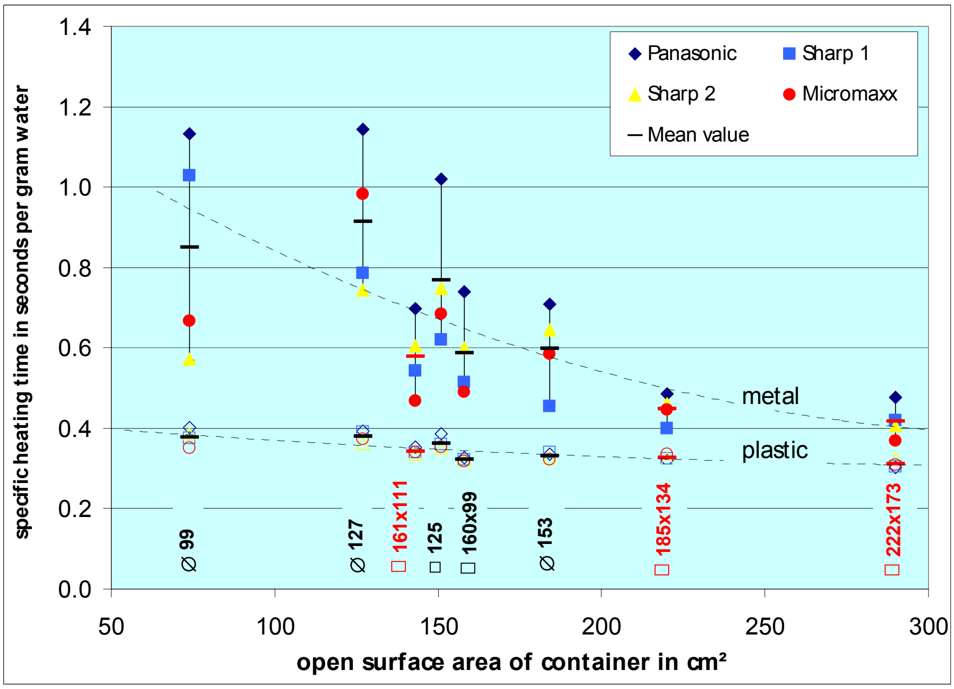


Figure 6.6: Results on specific heating time in seconds per gram tap water, normalised for a 1000 W oven. Values of other metal containers from a previous study are included and marked red.

The display of specific heating times will be also used below to present the results of experiments with “chili con carne” and infant meal. Figure 6.5 therefore allows making some comparison between experiments with real foods and tap water.

Heating Experiments with Real Food

Experiments with real food show significant differences to heating experiments with tap water.

Heating experiments with real food were set up differently from heating experiments with tap water. The heating covered a full temperature increase from 10°C start temperature to about 75°C end temperature. In experiments with tap water only a small temperature increase around room temperature was applied in order to avoid heat exchange with the environment by convection and evaporation. Heating of food to a serving temperature of 75°C involves significant heat losses by convection and evaporation. These heat losses are part of the energy balance but do not show up, if temperature increase of the food portion is measured. They will be discussed later on.

In Figure 6.7 the real heating times are displayed that were used with the different oven/container combinations to heat “chili con carne” from a start temperature of about 10°C to an average end temperature of about 75°C.

The first conclusion that can be drawn is that heating times for food in metal containers are considerably longer than for food in plastic containers. For most of the metal containers, a heating time by a factor between 1.6 to 2.0 longer than for similar plastic containers is necessary to achieve the desired heating effect. In case of the smallest container, the factor is about three.

If values of actual heating times are transformed into specific heating times per gram of food filling in a 1000 W oven, then figure 6.8 follows. By normalising to a 1000 W oven, the effect of different nominal oven powers is cancelled and the large variation in heating times for the same metal or plastic container in different ovens is much reduced. Specific heating times for "chili con carne" in metal containers range from 0.7 seconds per gram to 1.2 seconds per gram food compared to about 0.4 seconds per gram for plastic containers.

Very similar results are obtained with infant meal as a test food. Figures 6.9 and 6.10 show measurements and calculations for this case. Actual heating times to achieve the desired heating effect are longer in metal containers by a factor of 1.7 to 1.9, for the smallest container the factor is 2.9 (figure 6.9). The specific heating times for infant meal in metal containers range from 0.6 seconds per gram to 1.1 seconds per gram compared to 0.4 seconds per gram for infant meal in plastic containers (figure 6.10).

Several interesting observations can be deduced from the presented measurement results and diagrams.

a) Figures 6.8 and 6.10 show that the influence of metal container size on heating performance is very noticeable. Per gram of food filling, heating is significantly faster in a large metal container. The tested plastic containers show a heating performance that is nearly independent of container size. In addition, the shapes of the metal containers seem to influence heating performance. Certain forms or aspect ratios seem to be favourable like container □**125**.

b) The transition from actual heating times (figures 6.7 and 6.9) to specific heating times (figures 6.8 and 6.10) reduces variation of heating times of a specific container in different ovens to a large extent. The reduction of variation is achieved by cancelling the different nominal oven powers. This suggests that the oven construction plays a smaller role in the case of metal containers filled with the used foods than in the case of metal containers filled with water. One exception is the smallest container ∅ **99**, which still shows a rather large variation of heating performance in different ovens.

   The reduced variation of specific heating times for the same metal container in different ovens are an interesting result since it opens the perspective to developing microwave heating instructions for food in metal containers that include oven power but are independent of oven construction. Still, every particular food product, be it packed in metal or in plastic containers, that is marketed for microwave heating, needs careful development of heating performance and heating instructions.

c) The difference between heating performance of water in metal containers (figure 6.5) on one side and “chili con carne” and infant meal in metal containers (figures 6.8 and 6.10) on the other side is very obvious. A direct comparison of both experiments is difficult, since the experimental setting is different and the strong evaporation losses as observed in the food heating experiments are practically nonexistent in the tap water heating.

   One effect of the heat losses by convection and evaporation is the longer specific heating time in the food heating experiments compared to the tap water experiments. Tap water in metal containers required 0.6 seconds per gram to 0.92 seconds per gram to be heated to 75°C in a 1000W oven. The two model foods needed significantly more with 0.65 seconds per gram to 1.22 seconds per gram (“chili con carne”) or 0.6 seconds per gram to 1.1 seconds per gram (infant meal). Even in the case of plastic containers, the specific heating time of 0.4 seconds per gram for the model foods is slightly higher than for tap water.

   A more surprising observation is the different behaviour of metal containers filled with tap water and metal containers filled with the test foods “chili con carne” and infant meal with respect to variation in specific heating times. The variation of specific heating times for the same water filled metal container in different ovens is quite large (figure 6.5) while it is much smaller for containers with food filling (figures 6.8 and 6.10). The deviation in heating performance suggests that the used model food/metal container combinations are less prone to influence from oven construction than the water/metal container combinations. The investigation of possible mechanisms behind the surprising effect was not part of the study.

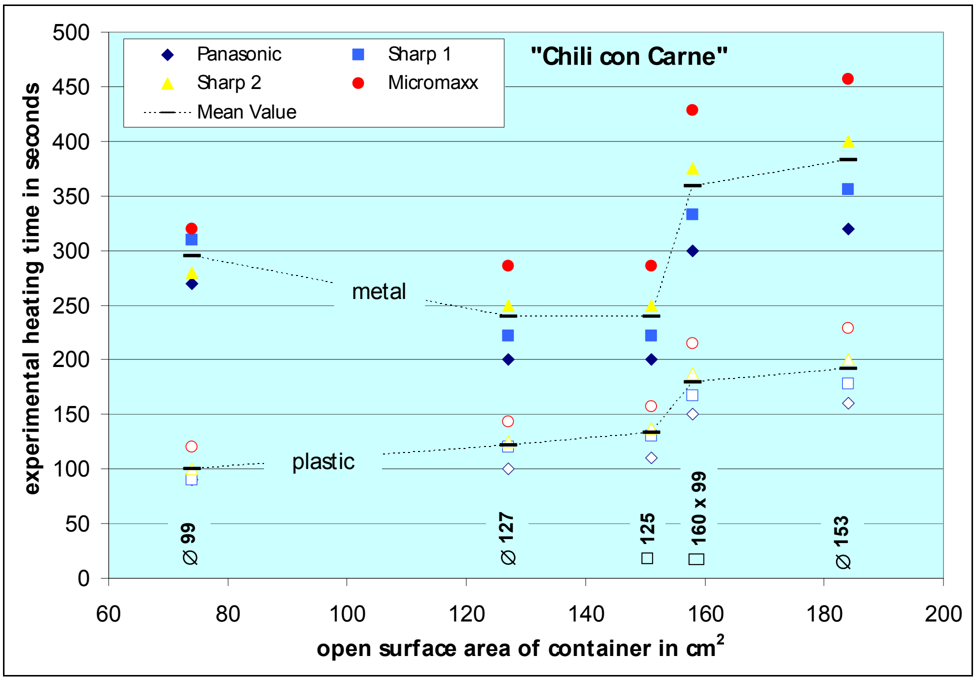


Figure 6.7: Used heating times in microwave heating experiments with containers filled with "chili con carne". The heating times were adjusted to achieve an average temperature increase from 10°C to 75°C.

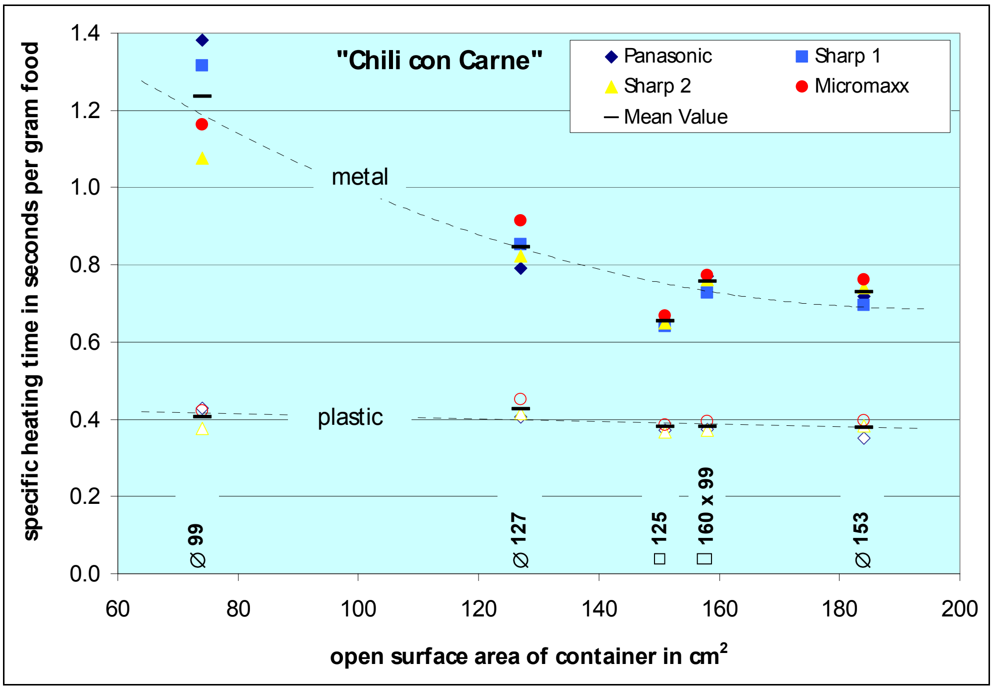


Figure 6.8: Specific heating time in seconds per gram product, normalised to a 1000 W oven. Values calculated from real heating times in figure 6.7.

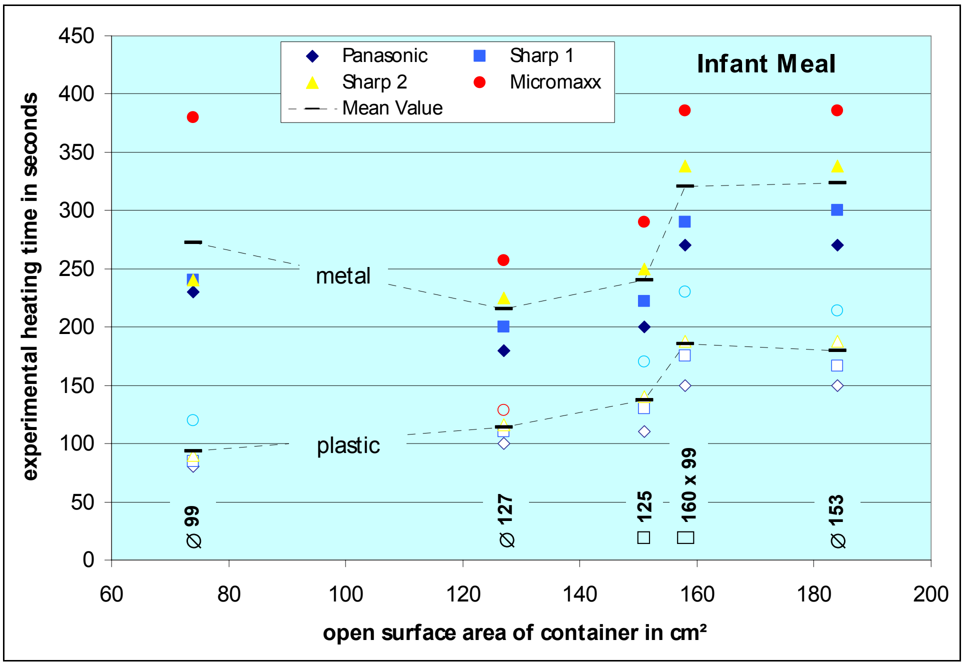


Figure 6.9: Used heating times in microwave heating experiments with containers filled with infant meal. The heating times were adjusted to achieve an average temperature increase from 10°C to 75°C.

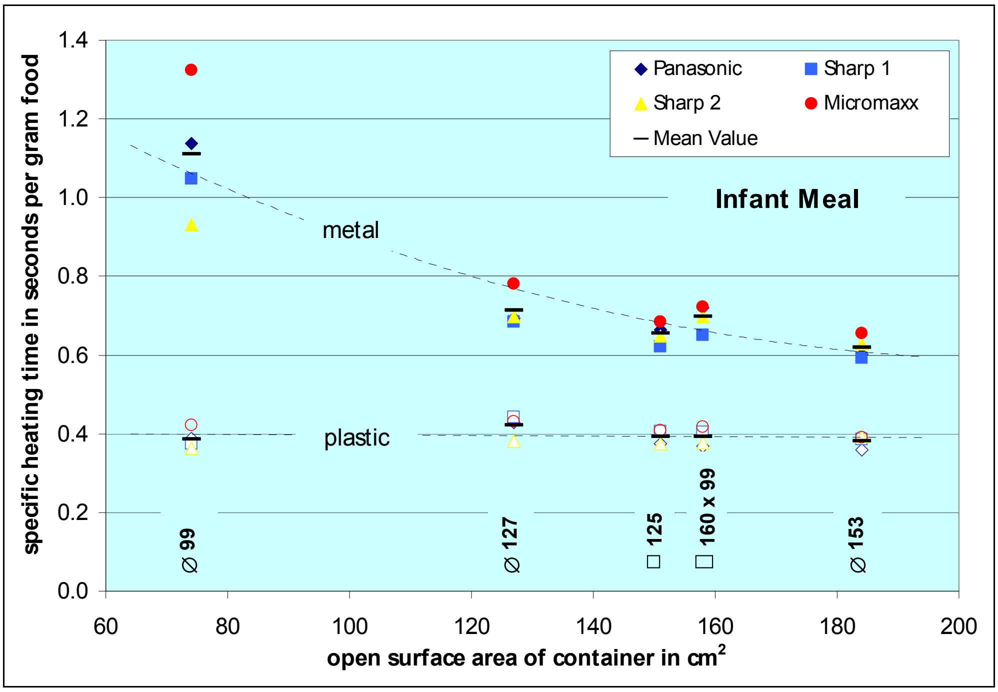


Figure 6.10: Specific heating time seconds per gram product and normalised to a 1000 W oven. Values calculated from real heating times in figure 6.9.

Evaporation

In all heating experiments with food, evaporation loss was measured by putting the food filled containers on a balance before and after microwave heating. The results of the evaporation loss measurements are shown in figures 6.11 and 6.12 as percentage of food filling.

Evaporation was higher in all experiments with metal containers compared to similar plastic containers. The reason for this observation are longer heating times for metal containers and the sole access of microwave energy to the food from the exposed and open surface which usually heats faster and is hotter than the rest of the filling. However, the different metal container shapes and sizes were differently affected by evaporation. In the two largest metal containers, evaporation in relation to food filling is high because of comparably long heating times (figures 6.7 and 6.9) and large exposed surface. In the smallest container (∅**99**), the evaporation was also high due to long heating times in relation to mass of food filling. In the two medium sized containers (∅**127** and □**125**) the evaporation in relation to food filling was lower. In the case of the plastic containers, evaporation in relation to food filling was fairly independent of container size.

The energy needed to evaporate water is more than ten times higher than the energy to warm-up water from 10°C to 75°C. Therefore even small quantities of evaporated water contribute significantly to the energy balance of the heating process. The energy used up for evaporation from food during microwave heating was calculated and is shown in table 6.5. The values are given as thermal evaporation energy in relation to the thermal energy needed to heat the food portion from 10°C to 75°C.

The calculated values are in fact impressive. In the case of metal containers, more than 50% of the energy amount that goes into temperature increase of the food is on average lost to evaporation. In the case of plastic containers, it is still more than 25% of the food heating energy. Obviously, this energy loss contributes to the extension of heating times needed for the desired heating to serving temperature. Since evaporation is about twice as high in metal containers than in plastic containers, the effect on total heating times is also higher. Therefore the long heating times for food in metal containers may in part be explained by the higher rate of evaporation.

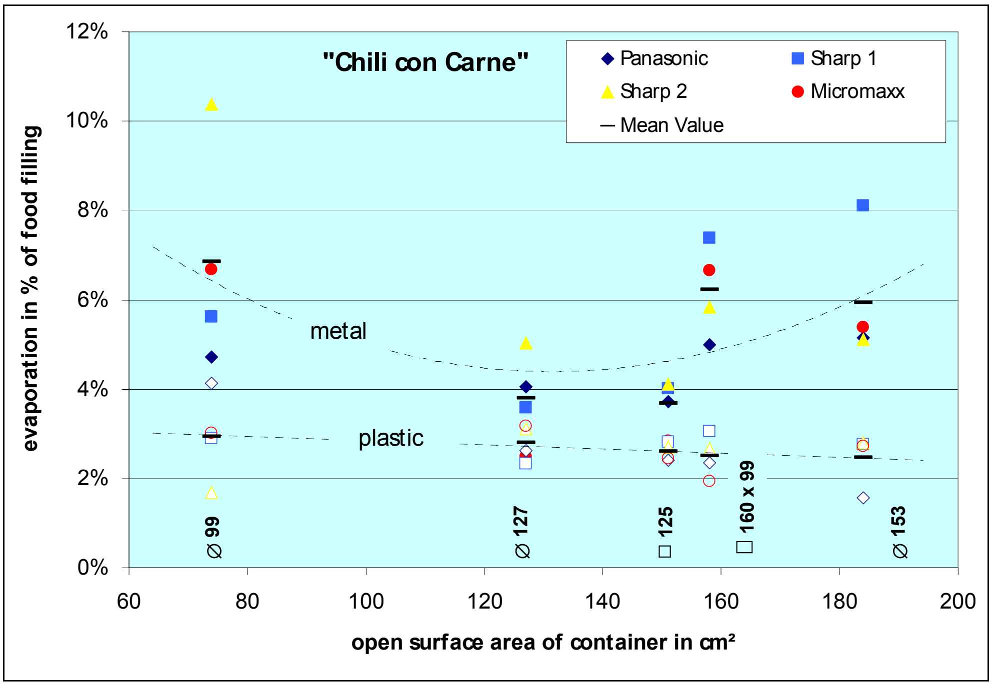


Figure 6.11: Water evaporated from "chili con carne" during microwave heating in percent of mass of food filling.

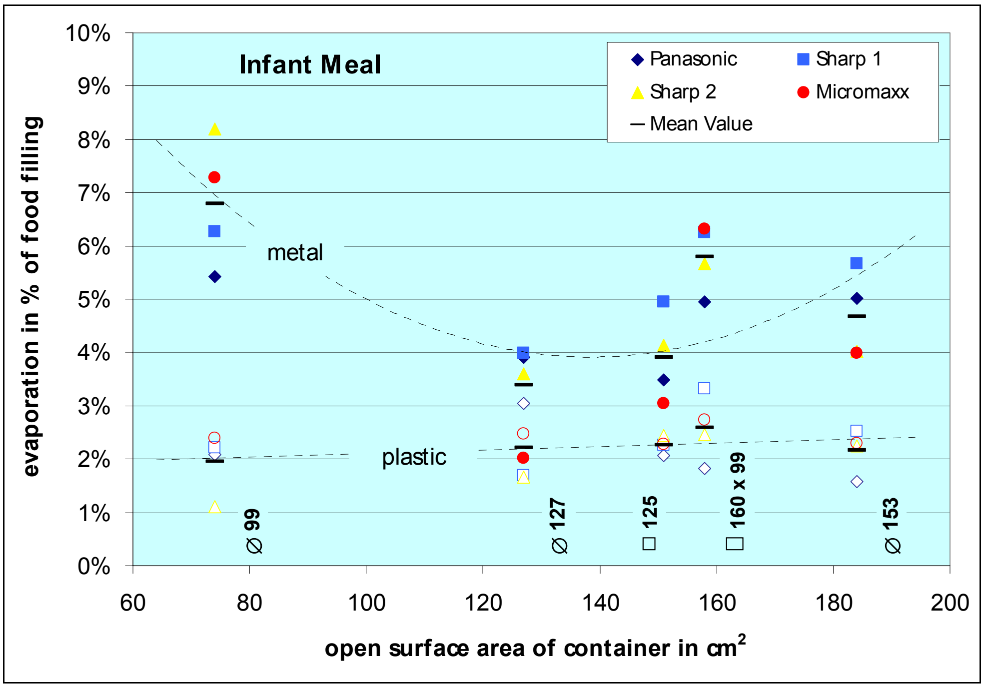


Figure 6.12: Water evaporated from infant meal during microwave heating in percent of mass of food filling.

Table 6.5: Calculated evaporation energy in relation to energy needed to heat the food portion

Evaporation energy in relation to heating energy	**"chili con carne"**	**infant meal**
metal container	30…132% average: 64%	23…98% average: 56%
plastic container	18…47% average: 32%	17…36% average; 25%

The strong evaporation is most probably supported by the full power setting of the microwave ovens that was used in all experiments. Reduction of microwave power setting may therefore also reduce evaporation and consequently increase heating efficiency, since less energy is lost into transforming water to vapour. The resulting increase of necessary heating time will be less than proportional to reduction of power setting, if the assumption holds. This would in particular help in the case of metal containers and could reduce heating time difference in comparison to similar plastic containers. However no experiments have been performed to verify this estimation.

To get a complete energy balance, the energy share to heat the container material in the heating experiments has been estimated. Heating of container material contributes by a fraction of 1.2% to 1.7% to total consumption of thermal energy in the load (steel: 1.7%, aluminium: 1.2%, C-PET: 1.4%). In the energy balance, this contribution can be neglected.

6.3 Heating patterns and temperature distribution

Heating patterns and heating uniformity are important phenomena for microwave heated food that cannot be brought easily to an equilibrium temperature by stirring. In order to investigate heating patterns and heating uniformity, two different experiments were performed:

a) Liquid egg batter was microwave heated in the tested containers to partial solidification of about 50%. Then, the remaining liquid parts were removed by a spoon to make the shape of the solidified part visible. This gives a good visual impression of parts that heat rapidly in the microwave field. The void parts correspond to regions that heat slowly.

b) The qualitative experiment of a) was supplemented with a quantitative measurement of temperature distributions in containers filled with "chili con carne" and infant meal. 18 to 50 single temperature measurements were performed in each container in distinct patterns and two measurement heights above container bottom and evaluated. Besides the evaluation of average values for heating efficiency, heating patterns were extracted from the measurements as well as information on maximum and minimum temperature and on maximum temperature difference in one container.

The experiments were carried out with all tested metal containers and all their plastic equivalents in all four microwave ovens. But only patterns measured in two ovens, the Panasonic oven and the Micromaxx oven are included in the report. The heating patterns measured in the two Sharp ovens resemble the patterns measured in the Panasonic. Patterns measured in the Micromaxx oven were different and are therefore also presented.

Only a few characteristic measurement results are presented in this section of the report. A table containing a combination of results from both experiments was compiled and is shown in appendix A.

Experiments with egg batter

In the tested metal containers and in all ovens, the solidification of egg batter started at the surface of the filling. At the container bottom, heating is slower and the solidification takes place rather late. This can be seen in figure 6.13 for the ∅ **127** metal container in the Panasonic oven. In the smaller containers ∅ **99**, ∅ **127**, and □ **125**, heated in the Panasonic oven, there is also an additional liquid spot visible in the centre. In the metal containers heated in the Micromaxx oven, a liquid centre spot was absent (see figure 6.14).

Figure 6.13: Solidification of egg batter in ∅ **127** metal *container after 130 s in the* ***Panasonic*** *oven.*

Figure 6.14: Solidification of egg batter in ∅ **127** *metal container after 186 s in the* ***Micromaxx*** *oven.*

Figure 6.15: Solidification of egg batter in ∅ **127*** *plastic container after 60 s in the* ***Panasonic*** *oven.*

Solidification patterns looked quite different in plastic containers. Figure 6.15 shows the pattern that formed in the ∅ **127*** plastic container after 60 s heating in the Panasonic oven. The batter starts to solidify at the container wall. The centre region from bottom to top stayed liquid for a long time. The pattern that formed in the Micromaxx oven was very distinct as can be seen in figure 6.16. The solidification started in the centre of the container from bottom to top. In addition there was a solidification at the wall. In the circular area in between, the batter solidified very late. The pronounced centre heating of the Micromaxx oven was apparent in many heating experiments and distinguished that oven model from the other tested models.

For a complete overview of patterns in all containers obtained from heating experiments in the Panasonic and the Micromaxx oven, we refer to appendix A.

Figure 6.16: Solidification of egg batter in ∅ **127*** *plastic container after 86 s in the* ***Micromaxx*** *oven.*

Several heating experiments with egg batter were continued until the batter was completely solidified. In these experiments, complete solidification down to the container bottom and into corners was shown in all tested metal containers.

Measurements of temperature distribution in “chili con carne” and infant meal

Temperature distributions measured with the thermocouple array in containers filled with “chili con carne” and infant meal resembled largely the patterns obtained in the egg batter heating experiments. Figure 6.17 shows two measured temperature distributions in ∅ **127** metal containers filled with both foods and heated in the Panasonic oven.

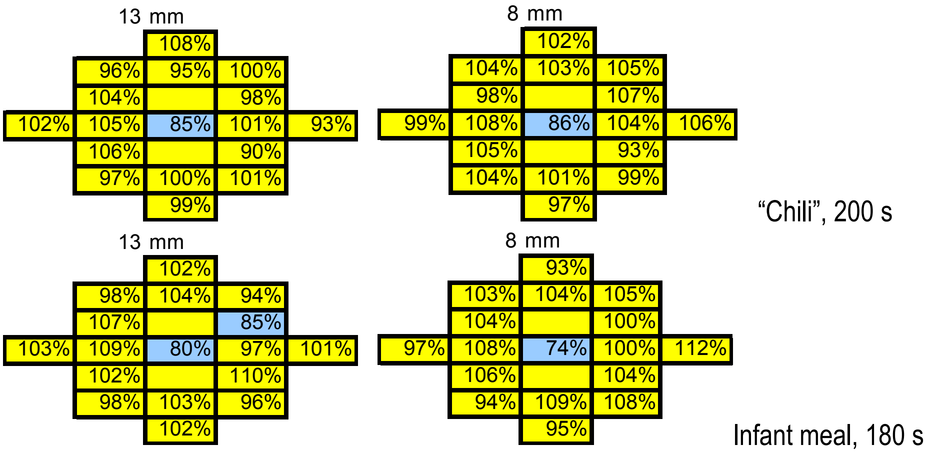


Figure 6.17: Measured temperature distributions in ∅ **127** *metal containers filled with both foods after 200 s and 180 s in the* ***Panasonic*** *oven. Temperatures are shown as percentage of average end temperature. Hot and cold spots are indicated by colouring: red - hot spot; blue - cold spot; yellow - intermediate temperature.) Each measurement consists of two planes in 8 mm and 13 mm height above support of container. The 13 mm measurement is near to filling surface, the 8 mm measurement is near to the bottom of the container.*

Main characteristic of both temperature distributions is a cold spot in the centre of the container. This resembles the egg batter pattern of figure 6.13. The remaining temperatures in the distribution are fairly uniform. Also a rather good temperature balance between upper and lower measurement plane can be observed. Extreme positions inside the container near wall, bottom and food surface are not included in the measurement and may deviate from the general picture of the measurement.

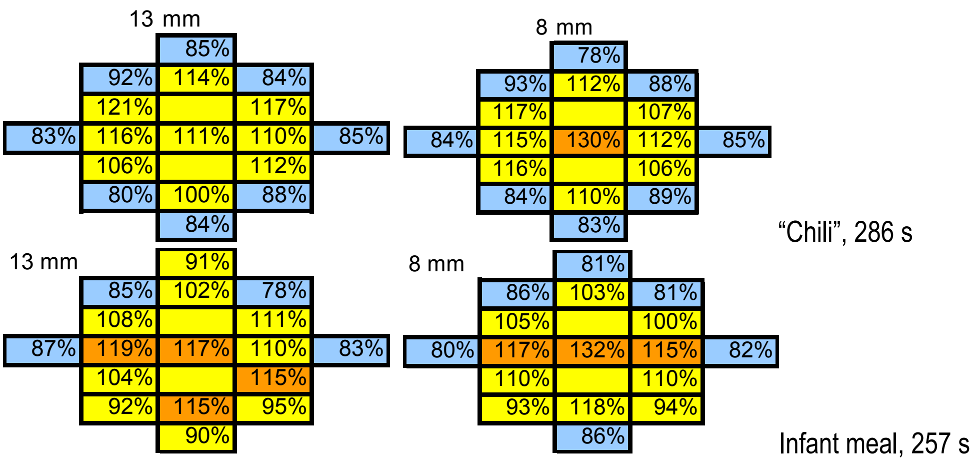


Figure 6.18: Measured temperature distributions in ∅ **127** *metal containers filled with both foods after 286 s and 257 s in the* ***Micromaxx*** *oven.*

Figure 6.18 shows the measurements with the same container after heating in the Micromaxx oven. In this case, the centre region was heated to rather high temperatures while the region near the wall of the metal containers is cooler. Again, a good balance of temperatures between upper and lower measurement can be observed. The highest measured temperatures were at the centre of the bottom, though the microwave access in the metal container was only from the surface. As in the previous measurement, positions outside the area captured by the measurement may deviate from the given picture.

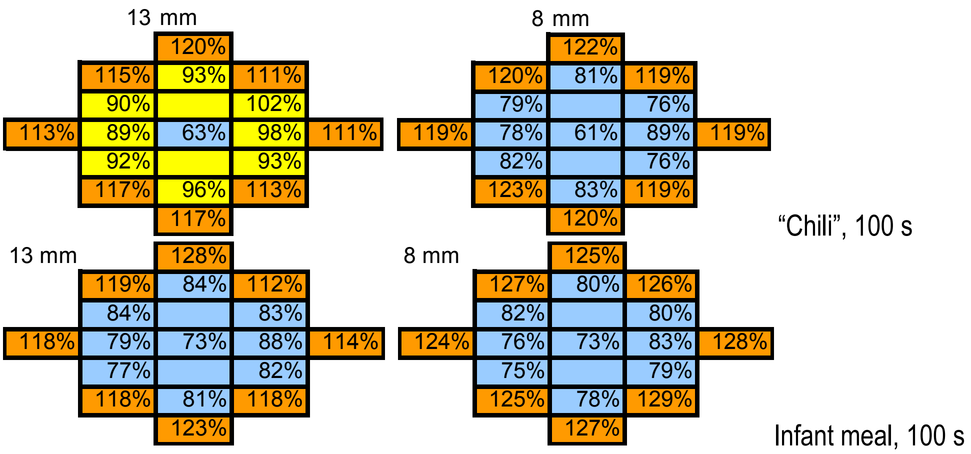


Figure 6.19: Measured temperature distributions in ∅ **127*** *plastic containers filled with both foods after 100 s in the* ***Panasonic*** *oven.*

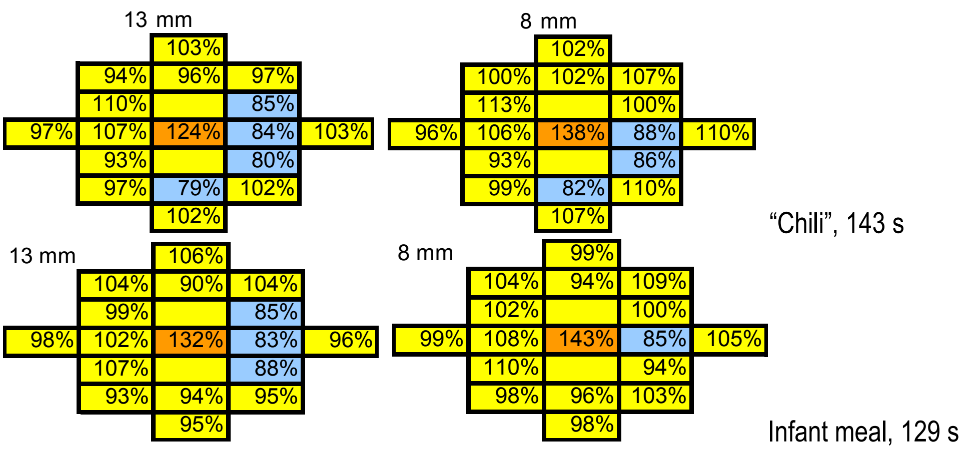


Figure 6.20: Measured temperature distributions in ∅ **127*** *plastic containers filled with both foods after 143s and 129 s in the* ***Micromaxx*** *oven.*

Temperature distributions measured in plastic containers were in many cases quite distinct from distributions measured in metal containers. Figure 6.19 shows distributions measured in the ∅ **127*** plastic container after heating in the Panasonic oven. Very high temperatures were reached at the container wall from bottom to surface. Most of the interior was much cooler. The corresponding result from an egg batter experiment (figure 6.15) shows a liquid centre that extends from surface of filling to the bottom of the plastic container.

Temperature distribution measured after heating in the Micromaxx oven with its tendency to centre heating, showed a pronounced hot spot in the centre (figure 6.20). The region at the wall is warm and between centre and wall is a cool region. This resembles very much the pattern obtained in the experiment with egg batter (figure 6.16).

In conclusion, it can be said that both, experiments with egg batter and with temperature distribution measurement, in metal containers as well as in plastic containers showed strong patterns with large difference between maximum and minimum temperature. These patterns result from electromagnetic resonance of the microwave field inside the food filling and cannot be avoided by moving the containers on the oven's glass turntable. Obviously, the compact food fillings used in the experiment formed an efficient resonator even without the reflecting boundaries of the metal container.

The actual form of the heating pattern depends on container material (metal or plastic), on container geometry and on oven construction. Also the food filling has an influence. Compact fillings like those of the tested model foods behave differently from fillings consisting of particles with air in between. We also noticed that rough surface structures with single particles protruding from the surface of the otherwise compact filling, provided different heating results than the smooth surface water fillings and helped to bring microwave energy into the metal containers.

Heating patterns and temperature distributions in metal containers showed in most instances lower temperatures near the container wall than in the rest of the container. Lowest temperatures were measured at corners and edges of the container bottom. In several cases, a small cold spot developed in the centre of the tray. The Micromaxx oven was different, since in nearly all containers, metal as well as plastic, a pronounced hot spot developed in the container centre. In plastic containers very high temperatures were measured at the container wall, while temperatures in the centre region were significantly lower. Exception was again the Micromaxx oven where in addition to high temperatures at container walls, a hot spot developed in the centre surrounded by an annular region of lower temperatures.

Though in metal containers, the access of microwave energy is only from the open upper side, in containers ∅ **127** and □ **125** the temperatures in the upper and lower measurement plane were very similar. This may be attributed to a shallow filling of 20 and 22 mm and to wide open diameters >125 mm. In ∅ **99** and in ▯ **160x99** containers, higher temperatures were measured near the filling surface. In both cases, filling was higher with 30 mm and 26 mm, and the cross section, at least in one dimension, was small with only 99 mm. The ∅ **153** container with 26 mm filling height and a large diameter showed a mixed picture. With “chili con carne” upper and lower temperature levels were balanced; with infant meal temperatures near surface were higher.

Generally, measured temperature variations were smaller in metal containers than in plastic containers. Figures 6.21 and 6.22 show the maximum measured temperature difference in all tested containers with “chili con carne” and infant meal. With both food fillings maximum temperature difference is significantly lower in metal containers. This is in particularly visible with “Chili con carne” (figure 6.21), where a temperature difference between 20°C and 40°C was measured in metal containers while a difference between 40°C and 50°C was measured in plastic containers.

It is evident, that the longer heating times needed to warm up food in metal containers support temperature equilibration by internal heat transfer.

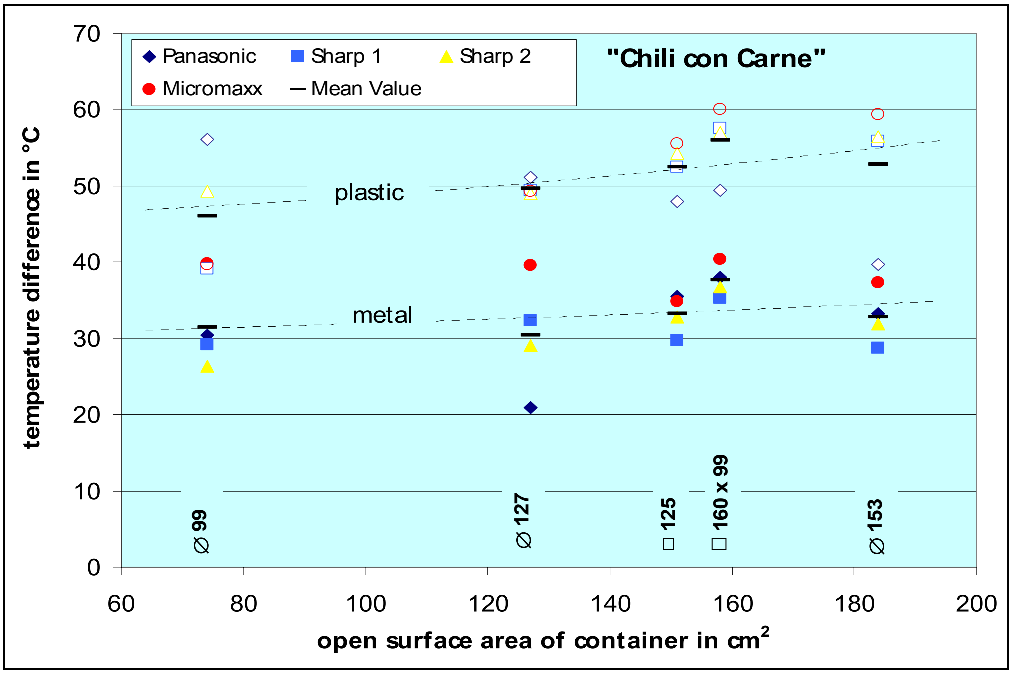


Figure 6.21: Maximum temperature variation in metal and plastic containers after microwave heating. Filling: “chili con carne”.

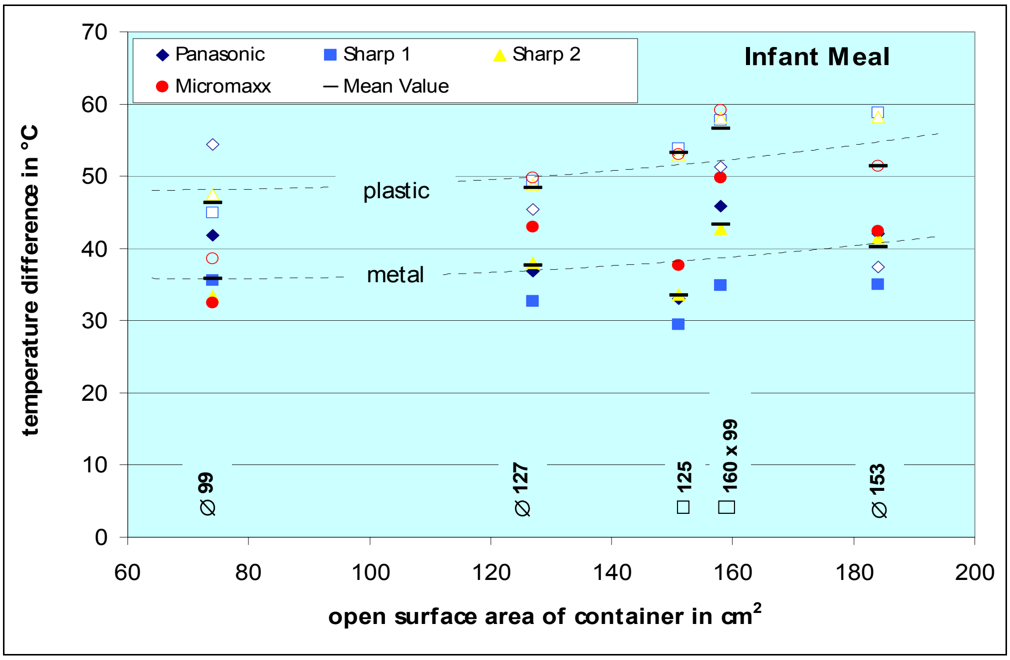


Figure 6.22: Maximum temperature variation in metal and plastic containers after microwave heating. Filling: infant meal.

6.4 Stability of oven performance

In order to test if use of metal containers would negatively affect the performance of microwave ovens, the power output of the four used ovens was measured according to a standard procedure (STANDARD 1999) before and after the extensive heating experiments.

Table 6.6 gives an overview on the experimental use of the microwave ovens in the reported study as well as in an earlier study. Per oven about 435 single heating experiments were performed. 250 of these were experiments with metal containers; 20 additional experiments were performed with aluminium household foil and other metal items. Included in the experiments with metal containers are 50 experiments with small containers (∅ **99)** and about 90 misuse experiments, where in many cases empty containers were put into ovens at full power. Our laboratory use of the ovens was quite harsh and did not care much about the instructions of the oven manufacturers.

Table 6.6: Accumulated use per microwave oven during heating experiments, including a previous study with other metal containers.

Estimated use per oven since purchase in mid 2005	steel, alu	of which misuse	of which small	other alu	plastic	**total count per oven**
earlier study	55	30		20	30	105
other experiments	15	10			25	40
actual study	180	50	50		110	290
sum of single heating experiments	250	90	50	20	165	**435**

Despite the challenging use of the ovens, we did not observe a single case of failure or significant loss of output power. Figure 6.23 shows the results of power measurements before and after the experimental program. In ovens Micromaxx and Sharp 2, no change in output power could be detected. Ovens Panasonic and Sharp 1 may show a slight decrease of output power by 4% and 3%. The change is still within the limits of measurement tolerance and is therefore not significant.

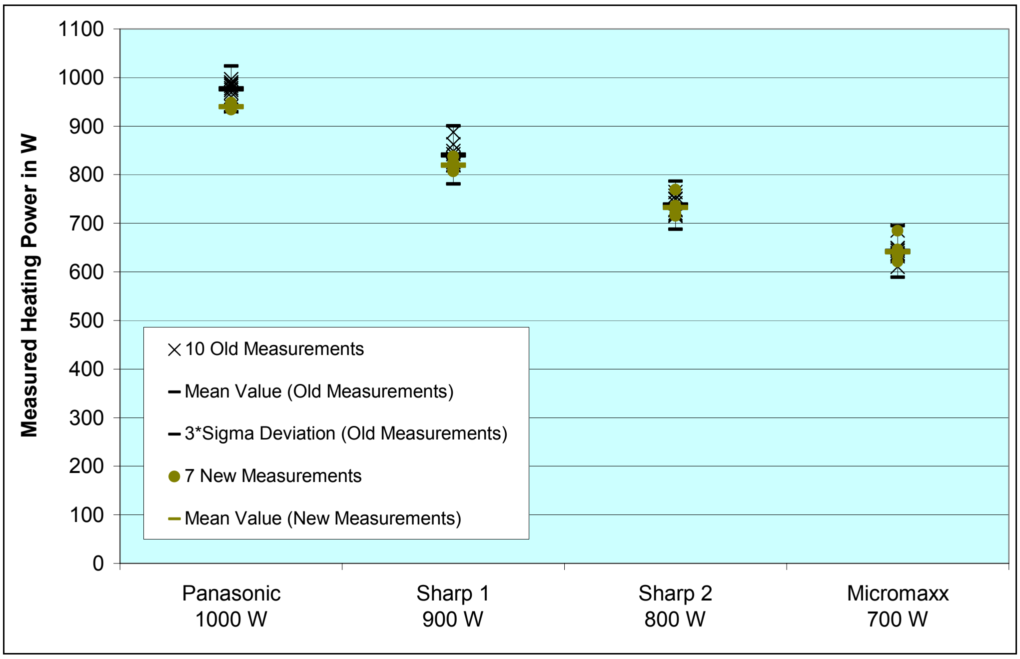


Figure 6.23: Measured microwave power output of four ovens used in the experiments. Measurements were done before and after the extensive heating experiments.

Concluding from our power measurements, we do not expect a negative effect on oven performance by use of metal containers of the tested forms. To completely exclude increased degradation of oven power by use of metal containers, a longer term experiment would be needed.

7 Conclusions

Safety and oven stability

The tested metal containers can be heated safely in microwave ovens, if ovens are operated in a standard way and some simple and basic rules for handling of containers are respected. During about 1000 microwave heating experiments with normal handling of metal containers, not a single occurrence of a spark or a potentially risky situation was observed. Furthermore, in many misuse experiments with non-standard handling of containers, where sparks were created intentionally and the microwave ovens were operated with empty containers, no oven was damaged and no situation with potential safety risk to the oven operator resulted.

Also oven performance was unaffected by the extensive and harsh use in the laboratory. In two ovens, not the slightest decrease of power output was detected after the experimental program. In the two other ovens, a decrease of 3% to 4% was detected, which is still within the limits of measurement error.

We conclude therefore, that the use of shallow and wide open metal containers for heating of food in microwave ovens is perfectly viable from a safety point of view, as long as some basic rules of microwave oven operation are respected.

Heating times

It was expected from physical considerations and it is known from a number of earlier studies, that in order to achieve a similar heating effect, longer microwave heating times are needed for food in metal containers compared to food in similar plastic containers. The relation measured in many heating experiments was between 1.7 for the largest metal container to about 3 for the smallest container. The larger the metal container the smaller is the difference in heating times between metal and similar plastic container.

A large influence of oven construction on heating times with metal containers was observed in a series of experiments with water filling. In heating experiments with "chili con carne" and infant meal in metal containers, the influence of oven construction seemed to be much smaller. In this practical heating situation, heating time variations between ovens for a specific container were rather small. It seems therefore possible to develop microwave heating instructions for food in metal containers that respect different nominal oven powers but are fairly independent of different oven constructions. This applies at least to food similar to the used model foods "chili con carne" and infant meal.

The analysis of evaporation from the food filling during microwave heating made it clear, that a large part of the absorbed microwave energy is not used for food heating but is lost into evaporation. Consequently, a longer heating time is required to heat the food to serving temperature. Since evaporation measured in metal containers is about twice as high as in similar plastic containers, the effect on extension of heating times is more significant for metal containers. We suspect that heating with full power setting - as it was the case in all heating experiments of the study - forces evaporation. Lower power settings for heating food in metal containers could possibly be an option to reduce evaporation and to improve heating efficiency. We expect that heating time will increase by this measure but less than proportional to the power reduction.

Heating patterns and heating uniformity

Strong heating patterns with large temperature variations were observed in both, plastic as well as metal containers. Heating patterns and temperature distributions in metal containers showed in most instances lower temperatures near the container wall and the container bottom than in the rest of the container. The lowest temperatures were measured at corners and edges of the container bottom. In plastic containers, very high temperatures were measured at the container walls, while temperatures in the centre region were in most cases significantly lower.

Measured temperature variations were significantly smaller in metal containers compared to plastic containers. The longer heating times for food in metal containers certainly support temperature equilibration and heating uniformity. It also seems that large open diameters of metal containers and low filling heights support uniform heating. In particular the balance between temperatures near the container bottom and near the filling surface was good in the medium sized containers that also had a shallow filling with 20 mm and 22 mm.

Small diameters and cross sections as well as filling heigts of 30 mm and above seem to result in more uneven heating. In the smallest metal container with 99 mm open diameter and 30 mm filling height, temperatures nearer to the container bottom were significantly lower than temperatures nearer to the filling surface. A similar large temperature difference was observed in the □**160x99** container with 26 mm filling height.

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Appendix A: Heating patterns and temperature distributions

The experiments with egg batter and temperature distribution measurements were carried out with all tested metal containers and their plastic equivalents in all four microwave ovens. But only patterns and temperature distributions measured in two ovens, the Panasonic oven and the Micromaxx oven are included in the report. The heating patterns measured in the two Sharp ovens resemble the patterns measured in the Panasonic oven. Patterns measured in the Micromaxx oven were different and are therefore included in the table.

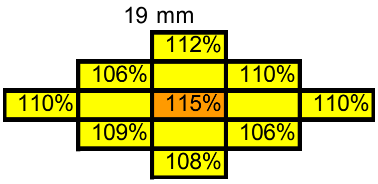
Patterns of solidified egg batter are presented as photos. Measured temperature patterns are presented as arrays of numerical values. The number arrays resemble the pattern of temperature measurement points (see also table A.1) in the container. These values are measured temperatures at the end of microwave heating which are related to the average end temperature of the food portion. Values significantly above 100% denote end temperatures significantly above average end temperature or hot spots and are marked red. Values significantly below 100% denote end temperatures significantly below average end temperature or cold spots and are marked blue. The millimetre values above the value arrays indicate the measurement position above the support of the container. This equals the position above the bottom of container minus 1 millimetre. Also indicated in the table are the applied heating times for egg batter, “chili con carne” and infant meal.

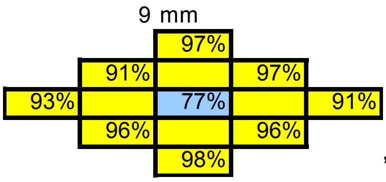
Table A.1: Heating patterns visualised by egg batter experiments and by multipoint temperature measurements.

∅ 99 in Panasonic

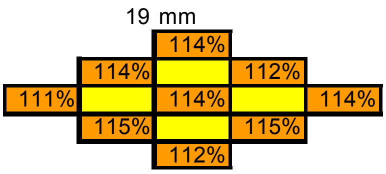
Egg Batter, 115 s

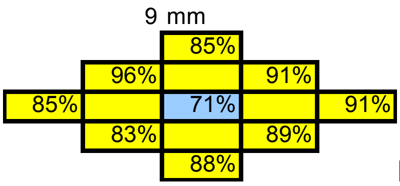
Liquid material in centre and near bottom. Surface centre surrounded by area of higher temperature.





"Chili", 270 s





Infant meal, 230 s

Higher temperatures near surface, lower temperatures near bottom. Cold spot in bottom centre.

∅ 99 in Micromaxx

Egg batter, 164 s

Solidification at surface, liquid at bottom and most part of wall.

19 mm

		103%		
	106%		103%	
108%		119%		101%
	108%		105%	
		103%		

9 mm

		94%		
	93%		90%	
96%		104%		94%
	88%		93%	
		94%		

"Chili", 320 s

19 mm

		101%		
	106%		104%	
108%		122%		107%
	109%		110%	
		106%		

9 mm

		91%		
	86%		88%	
85%		114%		92%
	84%		93%	
		94%		

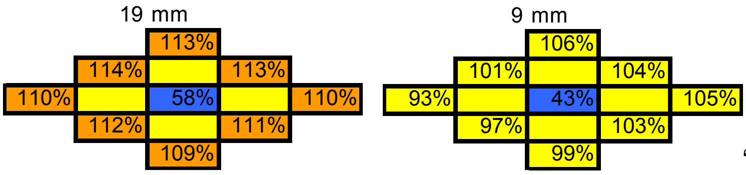
Infant meal, 380 s

Warmer near surface, cooler near bottom. Hot spot in centre, cold spot at bottom near wall.

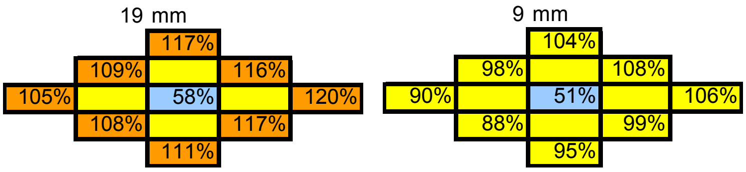
∅ 99* in Panasonic


Egg Batter, 50 s

Liquid material round centre surface and bottom (eccentric location of cold spot), solidification near wall.



"Chili", 90 s



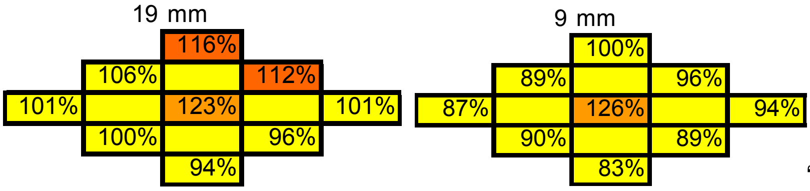
Infant meal, 80 s

Cold spot in centre bottom and surface, hot spot near wall at surface.

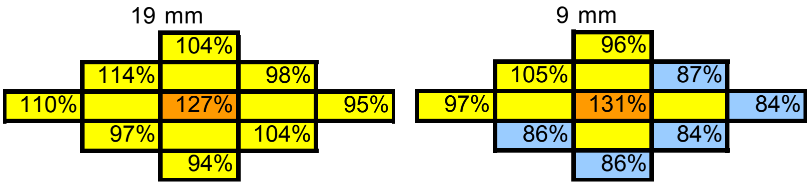
∅ 99* in Micromaxx


Egg Batter, 65 s

Strong solidified spot in centre extending from bottom to surface, nearly no solidification near wall.



“Chili”, 120 s



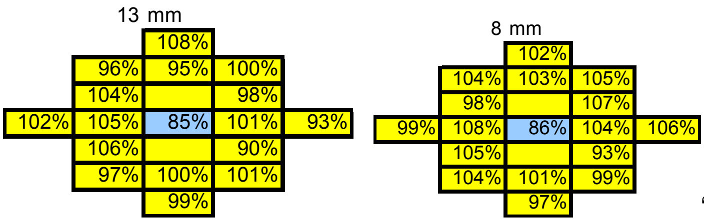
Infant meal, 120 s

Strong hot spot in centre from surface to bottom, cold spot near wall in particular at bottom.

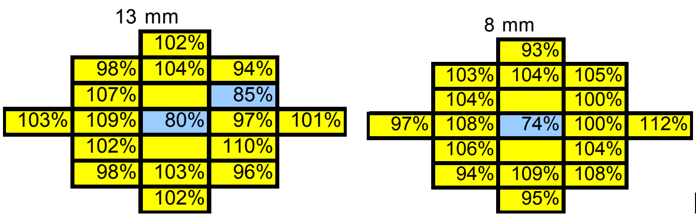
∅ 127 in Panasonic

Egg Batter, 130 s

Solidification at surface, eccentric cold spot, liquid at bottom.



“Chili”, 200 s



Infant meal, 180 s

Cold spot at centre surface and bottom, fairly uniform in rest of container. Similar temperature level in upper and lower plane.

∅ 127 in Micromaxx

Egg Batter, 186 s

Solidification at surface, liquid at bottom and directly at wall.

13 mm

		85%		
	92%	114%	84%	
	121%		117%	
83%	116%	111%	110%	85%
	106%		112%	
	80%	100%	88%	
		84%		

8 mm

		78%		
	93%	112%	88%	
	117%		107%	
84%	115%	130%	112%	85%
	116%		106%	
	84%	110%	89%	
		83%		

“Chili”, 286 s

13 mm

		91%		
	85%	102%	78%	
	108%		111%	
87%	119%	117%	110%	83%
	104%		115%	
	92%	115%	95%	
		90%		

8 mm

		81%		
	86%	103%	81%	
	105%		100%	
80%	117%	132%	115%	82%
	110%		110%	
	93%	118%	94%	
		86%		

Infant meal, 257 s

Hot spot at bottom centre, cold spot near wall at surface and bottom. Similar temperature level in upper and lower plane.

∅ 127* in Panasonic


Egg Batter, 60 s

Solidification at surface and wall, liquid in centre region.

13 mm

		120%		
	115%	93%	111%	
	90%		102%	
113%	89%	63%	98%	111%
	92%		93%	
	117%	96%	113%	
		117%		

8 mm

		122%		
	120%	81%	119%	
	79%		76%	
119%	78%	61%	89%	119%
	82%		76%	
	123%	83%	119%	
		120%		

“Chili”, 100 s

13 mm

		128%		
	119%	84%	112%	
	84%		83%	
118%	79%	73%	88%	114%
	77%		82%	
	118%	81%	118%	
		123%		

8 mm

		125%		
	127%	80%	126%	
	82%		80%	
124%	76%	73%	83%	128%
	75%		79%	
	125%	78%	129%	
		127%		

Infant meal, 100 s

Hot spot region at wall - surface and bottom, cool region round centre, centre cold spot with “chili”.

∅ 127* in Micromaxx


Egg Batter, 86 s

Solidification in centre and directly at wall, liquid in concentric region between centre and wall.

13 mm

		103%		
	94%	96%	97%	
	110%		85%	
97%	107%	124%	84%	103%
	93%		80%	
	97%	79%	102%	
		102%		

8 mm

		102%		
	100%	102%	107%	
	113%		100%	
96%	106%	138%	88%	110%
	93%		86%	
	99%	82%	110%	
		107%		

“Chili”, 143 s

13 mm

		106%		
	104%	90%	104%	
	99%		85%	
98%	102%	132%	83%	96%
	107%		88%	
	93%	94%	95%	
		95%		

8 mm

		99%		
	104%	94%	109%	
	102%		100%	
99%	108%	143%	85%	105%
	110%		94%	
	98%	96%	103%	
		98%		

Infant meal, 129 s

Strong hot spot in centre – surface and bottom; warm region near wall; cool region between centre and wall.

☐ 125 in Panasonic



Egg Batter, 115 s

Solidification at surface, liquid at bottom, small liquid spots in surface centre and surface corners.

14 mm

98%	109%	104%	103%	98%
101%	111%	107%	107%	100%
96%	119%	91%	103%	101%
103%	101%	106%	78%	105%
91%	102%	99%	97%	92%

7 mm

87%	96%	102%	103%	90%
101%	103%	104%	108%	98%
106%	98%	100%	106%	105%
95%	111%	106%	110%	96%
83%	89%	98%	96%	88%

“Chili”, 200 s

14 mm

95%	106%	102%	97%	97%
100%	109%	110%	101%	97%
95%	117%	88%	100%	104%
101%	105%	106%	86%	104%
87%	102%	102%	104%	96%

7 mm

90%	97%	95%	100%	89%
109%	102%	107%	108%	92%
105%	98%	91%	101%	104%
94%	109%	104%	110%	97%
87%	100%	103%	103%	94%

Infant meal, 200 s

Cold spots in corners, upper measurement warmer than lower measurement, eccentric hot spot at surface. Similar temperature level in upper and lower plane.

☐ 125 in Micromaxx

Egg Batter, 164 s

Solidification in most part of surface, liquid at bottom and at wall.

"Chili", 286 s

14 mm

94%	97%	103%	102%	95%
105%	113%	110%	97%	89%
103%	119%	88%	103%	82%
104%	112%	107%	78%	112%
93%	112%	100%	93%	92%

7 mm

89%	87%	104%	93%	91%
100%	99%	113%	101%	82%
106%	105%	116%	109%	97%
94%	110%	112%	110%	98%
86%	105%	102%	89%	97%

Infant meal, 290 s

14 mm

91%	98%	99%	101%	87%
102%	113%	108%	109%	97%
93%	122%	91%	102%	105%
92%	104%	109%	86%	104%
90%	104%	95%	92%	89%

7 mm

88%	91%	97%	107%	81%
108%	112%	120%	118%	95%
98%	110%	119%	119%	109%
83%	106%	115%	107%	93%
81%	98%	94%	87%	82%

Cold spots at corners and part of edges, cold spot at centre of surface, hot spot near centre. Similar temperature level in upper and lower plane.

☐ 125* in Panasonic


Egg Batter, 70 s

Solidification at edges and partly at bottom, liquid in most part of centre region.

14 mm

121%	116%	108%	109%	118%
105%	88%	82%	87%	110%
105%	82%	73%	82%	104%
107%	86%	83%	82%	111%
113%	104%	107%	105%	120%

7 mm

128%	118%	114%	113%	126%
111%	80%	76%	76%	112%
108%	75%	73%	77%	106%
106%	76%	79%	75%	111%
118%	102%	106%	104%	126%

“Chili”, 110 s

14 mm

123%	109%	116%	109%	121%
105%	73%	73%	79%	119%
108%	68%	60%	72%	110%
120%	84%	70%	75%	113%
122%	104%	103%	107%	125%

7 mm

127%	115%	120%	120%	128%
113%	70%	69%	73%	123%
115%	68%	65%	67%	115%
118%	76%	74%	74%	113%
130%	107%	109%	114%	131%

Infant meal, 110 s

Hot spots at corners short edges, also at long edge at bottom of infant meal, very low temperatures in centre region.

☐ 125* in Micromaxx

Egg Batter, 100 s

Solidification in centre region and at walls, ring-shaped liquid area extending from bottom to top.

14 mm

128%	98%	92%	105%	124%
114%	70%	98%	80%	92%
99%	80%	110%	106%	89%
100%	76%	111%	85%	110%
125%	106%	97%	91%	120%

7 mm

134%	95%	88%	100%	132%
110%	59%	87%	70%	95%
99%	76%	130%	101%	88%
102%	64%	111%	85%	110%
128%	107%	97%	94%	132%

“Chili”, 157 s

14 mm

127%	100%	94%	113%	124%
108%	73%	81%	76%	104%
89%	90%	113%	84%	91%
98%	83%	97%	78%	114%
125%	100%	86%	91%	122%

7 mm

133%	103%	94%	118%	130%
115%	71%	85%	72%	107%
90%	98%	128%	84%	92%
97%	74%	97%	76%	116%
130%	107%	91%	101%	131%

Infant meal, 170 s

Hot spots in corners and in centre, concentric cold region between centre and wall.

□ **160x99 in Panasonic**

Egg Batter, 160 s

Complete solidification of surface and upper part, liquid at bottom.

14 mm

95%	111%	107%	112%	101%
101%	122%	107%	115%	107%
108%	122%	98%	102%	103%
111%	115%	116%	96%	114%
103%	115%	110%	111%	102%

7 mm

85%	98%	98%	105%	96%
87%	84%	94%	103%	89%
79%	86%	98%	102%	99%
84%	85%	89%	112%	75%
90%	88%	91%	85%	93%

"Chili", 300 s

20 mm

89%	111%	117%	113%	100%
102%	124%	123%	121%	102%
107%	129%	109%	119%	109%
112%	119%	121%	110%	110%
104%	121%	124%	122%	102%

9 mm

80%	90%	100%	90%	81%
73%	90%	97%	96%	70%
76%	95%	87%	102%	78%
68%	100%	85%	114%	70%
79%	86%	99%	93%	79%

Infant meal, 270 s

Large centred hot region at surface, much cooler near bottom, cooler at short edges, cold spot at edges of bottom region.

☐ 160x99 in Micromaxx

Egg Batter,229 s

Surface and upper portion of filling solidified, apart from small regions at wall, still liquid at bottom.

14 mm

81%	91%	108%	103%	83%
103%	121%	116%	113%	109%
100%	127%	88%	105%	100%
108%	124%	117%	95%	114%
82%	115%	107%	106%	85%

7 mm

79%	94%	91%	94%	76%
108%	85%	110%	100%	94%
102%	89%	118%	107%	107%
93%	104%	109%	111%	96%
75%	89%	101%	90%	78%

“Chili”, 429 s

20 mm

76%	102%	111%	106%	79%
94%	123%	127%	120%	115%
100%	131%	111%	108%	119%
102%	128%	112%	109%	125%
76%	106%	105%	98%	90%

9 mm

73%	92%	105%	88%	72%
83%	101%	120%	108%	93%
87%	98%	123%	108%	108%
75%	96%	112%	100%	89%
65%	84%	92%	78%	75%

Infant meal, 386 s

Large hot centre region, cold spots at corners and short edges, upper part of filling warmer than lower part.

□ 160x99* in Panasonic


Egg Batter, 85 s

Solidification near wall and partly at bottom, liquid in most art of centre region.

14 mm

112%	107%	98%	99%	109%
111%	87%	87%	83%	96%
111%	86%	79%	90%	100%
118%	94%	88%	82%	109%
112%	107%	99%	100%	118%

7 mm

127%	107%	100%	110%	127%
122%	73%	73%	69%	108%
123%	74%	77%	74%	116%
123%	77%	86%	78%	121%
126%	98%	100%	99%	130%

“Chili”, 150 s

20 mm

117%	106%	103%	103%	117%
110%	76%	83%	88%	96%
108%	76%	76%	91%	99%
117%	91%	71%	83%	113%
120%	98%	96%	104%	122%

9 mm

123%	109%	101%	108%	123%
116%	73%	77%	76%	105%
117%	78%	77%	82%	108%
125%	83%	81%	76%	121%
129%	105%	108%	107%	132%

Infant meal, 150 s

Hot region at short edges, large centre region with very low temperatures.

□ **160x99* in Micromaxx**


Egg Batter, 121 s

Solidification at edges and in small centre region, ring shaped liquid region from top to bottom.

14 mm

125%	105%	95%	100%	124%
112%	69%	91%	69%	102%
111%	65%	116%	96%	97%
118%	68%	116%	70%	112%
129%	98%	89%	80%	123%

7 mm

137%	106%	91%	107%	137%
121%	57%	83%	64%	101%
116%	57%	134%	86%	111%
120%	57%	112%	65%	106%
135%	92%	92%	85%	135%

"Chili", 215 s

20 mm

115%	101%	89%	95%	121%
117%	62%	78%	67%	104%
117%	65%	98%	81%	98%
124%	67%	118%	76%	109%
118%	106%	99%	83%	123%

9 mm

133%	102%	91%	101%	135%
123%	59%	79%	62%	111%
122%	62%	117%	80%	106%
125%	66%	117%	78%	108%
131%	113%	109%	103%	135%

Infant meal, 230 s

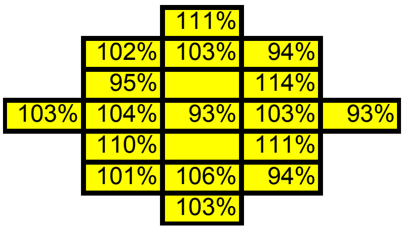
Hot regions near wall, in particular at short edge, hot spot in centre, cool region between centre and edges.

∅ 153 in Panasonic

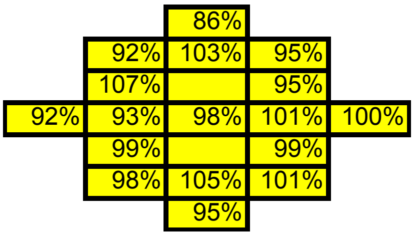
Egg Batter, 165 s

Complete solidification of upper part, liquid at bottom.

ɔrt: 15 mm

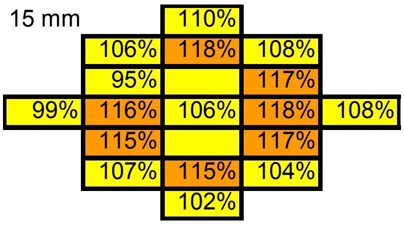


8 mm

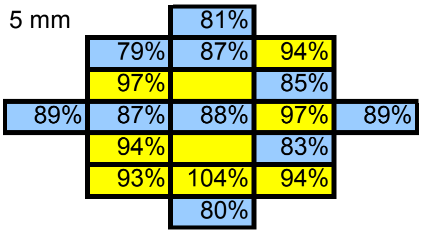


"Chili", 320 s

15 mm



5 mm



Infant meal, 270 s

Near surface warmer than near bottom, in particular in case of infant meal, concentric hot region visible at surface of infant meal.

∅ 153 in Micromaxx


Egg Batter, 236 s

Complete solidification of upper part, apart from small region at wall, liquid at bottom.

rt:

15 mm

		109%		
	102%	116%	90%	
	95%		109%	
106%	118%	100%	104%	76%
	111%		116%	
	99%	101%	75%	
		93%		

8 mm

		83%		
	98%	102%	95%	
	109%		105%	
93%	104%	109%	106%	87%
	107%		92%	
	95%	111%	87%	
		83%		

“Chili”, 457 s

15 mm

		123%		
	108%	118%	92%	
	95%		123%	
98%	119%	116%	107%	91%
	104%		112%	
	87%	103%	95%	
		91%		

5 mm

		91%		
	91%	113%	101%	
	98%		103%	
87%	99%	107%	101%	86%
	88%		82%	
	84%	83%	90%	
		83%		

Infant meal, 386 s

Near surface warmer than near bottom, cold region near wall at bottom.

∅ 153* in Panasonic

Egg Batter, 92 s

Solidification near wall and at centre of bottom, most of centre region liquid.

rt:

15 mm

		103%		
	105%	96%	105%	
	95%		96%	
110%	97%	110%	97%	105%
	102%		97%	
	115%	101%	114%	
		121%		

8 mm

		107%		
	100%	80%	112%	
	92%		75%	
106%	77%	112%	73%	111%
	80%		79%	
	119%	76%	114%	
		122%		

“Chili”, 160 s

15 mm

		106%		
	103%	94%	106%	
	95%		92%	
112%	105%	98%	93%	108%
	98%		90%	
	114%	98%	112%	
		120%		

5 mm

		112%		
	104%	81%	115%	
	77%		78%	
111%	86%	108%	78%	110%
	81%		80%	
	117%	84%	114%	
		121%		

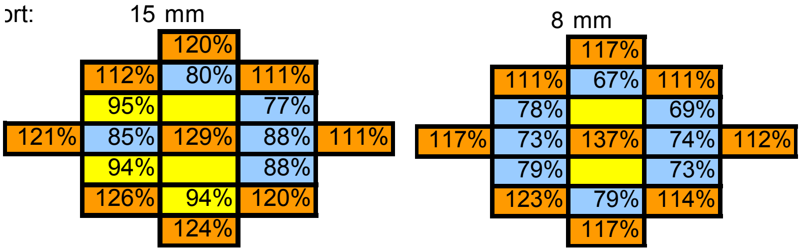
Infant meal, 150 s

Hot region near wall, concentric cold region in lower part.

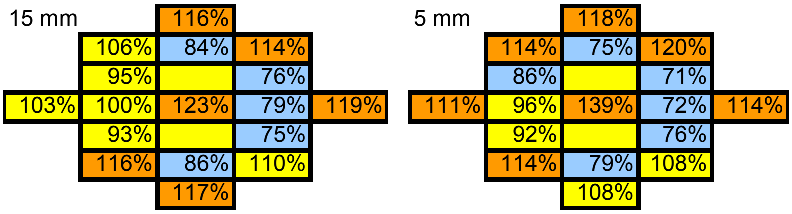
∅ 153*in Micromaxx

Egg Batter, 131 s

Solidified at wall and in centre, liquid in concentric region from bottom to surface.



“Chili”, 229 s



Infant meal, 214 s

Hot spot in centre, hot region at wall, concentric cold region between centre and wall.

Appendix B: Used microwave ovens

During expeditions through stores in the Munich area with electric appliances, the observation was made that all offered microwave ovens launch microwave energy through a window at the right side wall of the cooking chamber. This design seems to rule today's home microwave oven market. However, the mounting of the magnetron and the polarisation of the microwave field entering the cooking chamber can be different. Ovens with vertical arrangement of the magnetron antenna and ovens with horizontal arrangement of antenna were found. Four ovens were chosen for the heating experiments. Their main characteristics as stated in the data sheets are summarised in table B.1.

Table B.1: Microwave ovens used throughout the heating experiments.

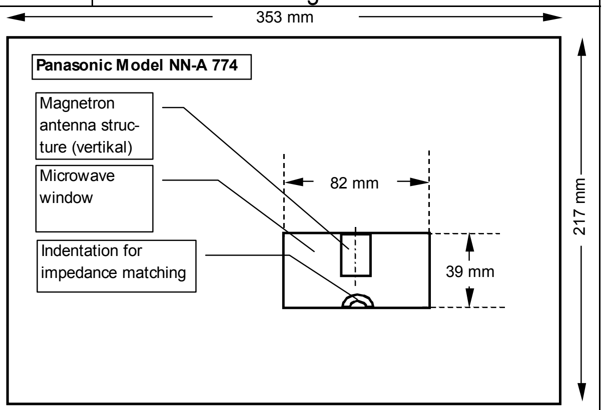
Manufacturer	**Panasonic**	**Sharp**	**Sharp**	**Medion**
Model	NN-A764 (Inverter oven)	R-734	R-208	Micromaxx MM 41580
Cooking chamber size (W/H/D) in mm	359/217/353	342/207/368	322/187/336	288/205/287
Volume of cooking chamber in l	27	26	20	17
Diameter of turntable in mm	340	325	272	245
Microwave power in W (data sheet)	1000	900	800	700
Power consumption in W (data sheet) without additional heating modes	1250	1370	1180	1150
Short name in report	Panasonic	Sharp 1	Sharp 2	Micromaxx

Specific characteristics, in particular the microwave window design are, shown in the following photos and drawings of figures 5.1 to 5.4.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with vertical antenna structure and indentation for electric impedance matching
(mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	1000 W
Volume of cooking chamber	27 l
Magnetron antenna orientation	vertical

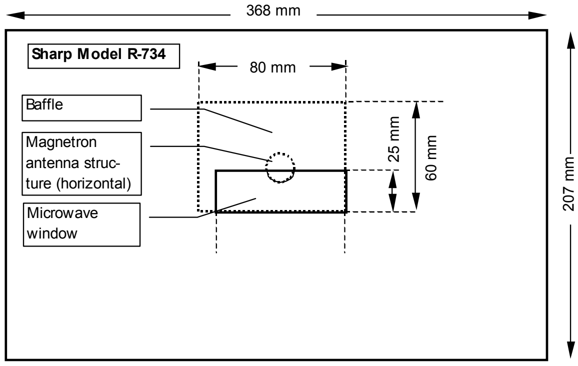
Figure B.1: Panasonic Microwave Oven Model NN-A764 - Inverter oven (Panasonic)

The Panasonic NN-A764 (figure B.1) is the oven with the highest power rating and the largest cooking chamber. The magnetron antenna is oriented vertical in the microwave window structure. A characteristic specific to the Panasonic oven is the power control. While in most ovens, microwave power is controlled via an on-off duty-cycle with adjustable on times, the Panasonic has a continuous electronic power control, termed “Inverter control” by the manufacturer.
The microwave window is situated rather low at the right side wall of the cooking chamber, the magnetron antenna is mounted vertical which gives the microwave energy radiating from the window a primarily vertical polarisation (vector of electric field is oriented vertically).

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with horizontal antenna and aperture baffle for electric impedance matching
(mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	900 W
Volume of cooking chamber	26 l
Magnetron antenna orientation	horizontal

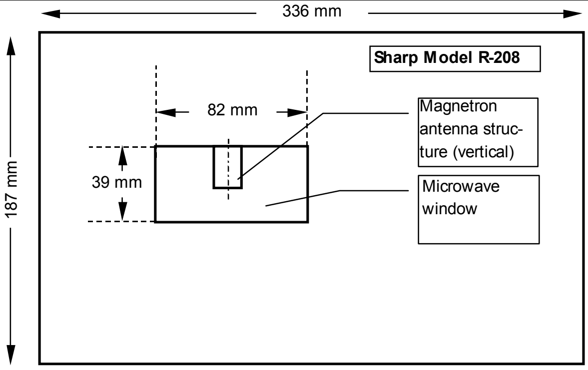
Figure B.2: Sharp Microwave Oven Model R-734 (Sharp 1)

Next smaller in size among the four ovens is the Sharp Model R-734 with 900 W rated microwave power (figure B.2). The microwave window is situated rather high at the right side wall of the cooking chamber. The magnetron antenna is mounted horizontally and separated from the cooking chamber by a reflecting baffle. The predominant polarisation of the radiated microwave energy is hard to predict without field calculation. It is however much less polarised vertically compared to the Panasonic oven.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with vertical antenna structure (mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	800 W
Volume of cooking chamber	20 l
Magnetron antenna orientation	vertical

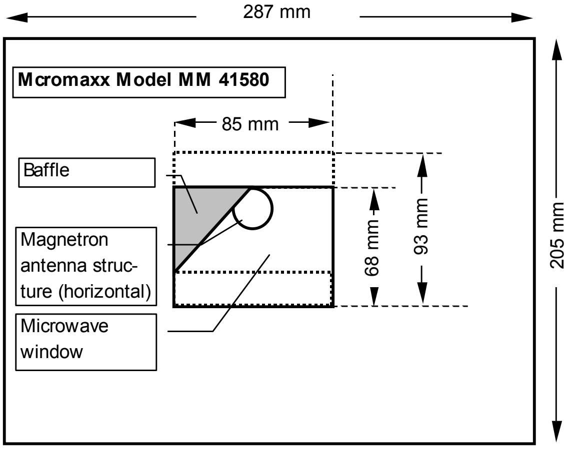
Figure B.3: Sharp Microwave Oven Model R-208 (Sharp 2)

The third oven is the Sharp Model R-208 with 800 W rated microwave power (figure B.3). The microwave window is situated rather high at the right side wall of the cooking chamber. The magnetron antenna is mounted vertically and the predominant polarisation of the radiated microwave energy is again vertical as in the Panasonic oven.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with horizontal antenna struc-ture and aperture baffle for electric impedance matching (mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	700 W
Volume of cooking chamber	17 l
Magnetron antenna orientation	horizontal

Figure B.4: Medion Microwave Oven Model MM 41580 (Micromaxx)

The last oven is the Micromaxx MM-41580 with a rated microwave power of 700 W (figure B.4). The microwave window is situated centred at the right side wall of the cooking chamber. The magnetron antenna is mounted horizontally and separated from the cooking chamber by a reflecting baffle. The predominant polarisation of the radiated microwave energy is hard to predict as in the case of the Sharp R-734, but is much less polarised vertically as in the Panasonic oven.