

Microwave Heating – the Influence of Oven and Load Parameters on the Power Absorbed in the Heated Load

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Abstract

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The microwave power is a parameter greatly influencing the rate of heating. Several authors reported on certain differences between the rated power output as a parameter used by oven manufacturers in the labelling of ovens, and the power actually delivered to the heated product. A review of the respective information is given in this article together with the results of own experiments following the influence of the oven type and the heated substance parameters on the power actually absorbed in the substance volume during its heating. As the heated substance, water and solutions of NaCl and sucrose of different concentrations were used. For the heating, four types of domestic microwave ovens and glass and plastic containers, were used. The decreasing of the efficiency of heating with the decreasing volume of the heated substance and a certain relation between the rate of this decrease and the types of oven and of substance was estimated. With the small cavity ovens, a lower rate of the decrease of the absorbed microwave power with the decreasing volume of the substance was found as compared to the large cavity oven. A certain influence of other technical oven parameters is shown in the comparison of the tests results with the ovens of the same rated power and the cavity volume. In addition to the substance volume, also its dielectric properties probably influence the microwave power absorbed in small samples during the heating. No simple dependence can be seen on the basis of the tests results between the type of container used in the tests and the power absorbed in the heated substance.

Keywords: microwave heating; microwave power; power absorption

Microwave power is a factor greatly influencing the rate of microwave heating. If a high value of power is applied, a high rate of temperature elevation in the heated body can be expected.

The dependence between the microwave power applied in heating and the increase of temperature can be described by the equation:

$$\Delta T = \frac{P \times t}{V \times c_p \times \rho} \quad (1)$$

where: ΔT – the increase of the mean temperature of the heated body (K)

P – microwave power used for heating (W)

V, c_p, ρ – volume, heat capacity, density (m^3 , J/kg.K, kg/m^3)

t – time of heating (s)

The manufacturers of microwave ovens give the value of the power output together with the microwave frequency

and the volume and dimensions of the oven cavity as the characteristics of an oven. The rated power output of the contemporary microwave ovens for household is in the range of 600 and 1000 W.

The calibration procedures based on calorimetric methods are used to obtain the value of the power output for microwave oven labelling. In Europe from 1990 year, there is a tendency to apply the procedure according to International standard IEC 705 (1988). In this methodology, 1 l cold ($10 \pm 2^\circ\text{C}$) potable water is heated in glass container of certain parameters and the time of $10 \pm 2^\circ\text{C}$ elevation of water temperature is measured. The microwave power absorbed in the water during the heating and used for its temperature elevation is calculated using Equation (1) adapted to the measurement conditions as (1a)

$$P = 4187 \frac{\Delta T}{t} \quad (1a)$$

Another recommendation for the estimation of the microwave oven power output gives IMPI standard designed in U.S. and used by many microwave oven manufacturers there. In this procedure, 2 l water at room temperature ($20 \pm 2^\circ\text{C}$) are heated in two glass beakers and the increase of water temperature during 2 min of heating is checked (BUFFLER 1992).

It was estimated, that the parameters of power testing – namely the amount of the heated water and its temperature – influence the results of testing, e.g. the value of the microwave power (BUFFLER 1992; GRÜNEBERG 1994). For example, because of the lower temperature of water before heating, IEC procedure gives a higher value of the power output than IMPI (1992) procedure for the same oven.

The value of the experimentally estimated power output is used for the labelling of microwave oven (rated power output) and can be used for the comparison of the performance of different microwave ovens. However, as follows from the experiments of some authors, this value does not enable to decide, how long a certain food product should be heated to obtain a certain temperature rise in the oven. Only part of the rated microwave power output, estimated at the heating of 1 or 2 l water load will be actually delivered to the food product of certain volume, geometry and physical properties and will be used for the elevation of its temperature.

The susceptibility of a food load to heating in a certain microwave oven depends on many factors probably connected both with the load parameter and the oven characteristics.

The value of the microwave power absorbed in the unit volume of the heated load (P_v) is described theoretically according to BUFFLER (1992) by Equation (2)

$$P_v = 2 \cdot \pi \cdot f \cdot \epsilon_0 \cdot \epsilon'' \cdot |E|^2 \quad (2)$$

where: P_v – power absorbed in the unit volume of the load (W/m^3)
 f – microwave frequency (Hz)
 ϵ_0 – permittivity of free space (F/m)
 ϵ'' – dielectric loss factor of the load – relative value (1)
 E – strength of the electric field inside of the load (V/m)

Except of the fixed parameters of microwave frequency (2450 MHz) and free space permittivity ($10^{-9}/36\pi \text{ F/m}$), the remaining parameters in the equation are related both to the load (ϵ'') and to the oven and the load (E).

The use of Equation (2) for the prediction of the absorbed power is problematic because of the parameter E . The prediction of the electric field distribution inside the load (local value of E) is extremely difficult because of the complexity of the interaction between the load parameters and the oven characteristics.

BUFFLER (1992) discussed all parameters possibly influencing the susceptibility of a certain load to heating in a certain microwave oven. According to him, the pa-

rameters with the greatest influence are magnetron (design) and the dimensions (volume) of the cavity as the parameters of the oven, and the volume and dielectric properties as the parameters of the heated load. The parameters that probably influence the microwave power absorbed in the heated load are the temperature of the load (influence on the dielectric properties), the geometry of the load (no known relationships to this time), the parameters of the package or container used in the heating of the load (temperature, heat capacity), the position of the load in the cavity (particular influence in the case of small loads), the cavity walls material (electric conductivity) and the feeding system (no known relationships).

According to BUFFLER (1992), the volume of the food load (or its volume with respect to the size of the oven cavity) has probably the largest effect of all food – related parameters.

Empirical relationship (3) was proposed by MUDGETT (1989) for the description of the dependence between the load volume and the power absorbed in the load

$$P_a = P_{\max} (1 - e^{-kV}) \quad (3)$$

where: P_a – power absorbed in the load of V volume (W)
 P_{\max} – oven power output (W)
 V – volume of load (m^3)
 k – volumetric coupling coefficient (1)

According to this relationship, the “coupling” of microwave power in the heated load decreases with the decrease of its volume. The rate of this decrease seems to be oven-specific, according to the experiments of several authors (SELLMAN 1991; BOWS 1990; BUFFLER 1992; RIWA *et al.* 1993; GRÜNEBERG 1994; PERSCH & SCHUBERT 1995).

The ratio r , defined as the power absorbed by 500 ml water to that absorbed by 1000 ml water, was proposed by BUFFLER (1992) as an indicator showing the oven power output falls with the load volume. According to him, a typical oven has $r > 0.8$.

The influence of the type of oven together with physical parameters of the heated loads on the absorbed microwave power was followed by GRÜNEBERG (1994). According to him, the ability of oven to heat the load of a certain volume is oven-specific. The volumetric coupling coefficient k from Equation (3) depends not only on the ratio between the cavity and the load dimensions, but also on some other oven characteristics (without specification). Also, the dielectric properties of the heated substance play a certain role in the relation between the absorbed power and the substance volume. Using Mie theory (MIE 1908), GRÜNEBERG (1994) formulated for this purpose a specific parameter, so called “absorption cross section” of substance, but a rather complicated calculation is needed for its estimation.

In the following text, the results are presented of our experiments following the ability of four household microwave ovens to heat different amounts of water and two water solutions. The influence of the type of container used in heating on the microwave power absorbed in the fluid during the heating is also discussed.

MATERIAL AND METHODS

Microwave ovens

Following microwave ovens were used in the experiments:

Moulinex, type FM 1515 E, rated power output 650 W, cavity dimensions $290 \times 175 \times 290$ mm, cavity usable volume 14.7 l, removable glass shelf on the cavity bottom, feeding of the cavity from the top.

Moulinex, type FM 2915Q, rated power output 850 W, cavity dimensions $330 \times 210 \times 343$ mm, usable cavity volume 23.8 l, removable glass shelf on the cavity bottom, feeding of the cavity from the top.

Samsung, type RE 576D, rated power output 650 W, cavity dimensions $300 \times 190 \times 290$ mm, usable cavity volume 16.5 l, glass turntable, feeding of the cavity from the top.

Whirlpool, type AVM 900/WH, rated power output 900 W, cavity dimensions $350 \times 228 \times 343$ mm, cavity volume 27.3 l, glass turntable, feeding of the cavity from the right wall (two places).

Heated substances (type and volume)

Potable water, volumes of 1200, 1000, 800, 600, 500, 300, 250 and 150 ml.

NaCl solution, concentrations of 2, 4 and 6% (20, 40 and 60 g NaCl in 1 l of solution), volumes of 1000, 500, 250 and 150 ml.

Sucrose solutions, concentration of 10 and 30% (100 and 300 g sucrose in 1 l of solution), volumes of 1000, 500, 250 and 150 ml.

Containers used for fluid heating

Glass vessel (SIMAX), round shape, inner diameter of 185 mm, height 78 mm, wall thickness 2 mm.

Glass beakers (SIMAX), cylindrical shape, rated volumes of 1000, 600, 500, 250, 150 mm.

Plastic trays (polypropylene PP) round and angular shape.

Dimensions of glass beakers and plastic trays are given in Table 1.

Measuring devices

Therm, type 2230-11 (AMR, Germany) with PT 100 probe was used for temperature measuring.

Digital watch DS 35 (Pragotron, CR) was used for time measuring.

Heating procedure

In the glass vessel, the heating of water of 1200, 1000, 800 and 600 ml volumes and the heating of solutions of both 1000 and 500 ml volumes was performed.

For the heating of smaller volumes of water and solutions, glass beakers were used.

For the heating of 350 ml water, plastic trays were used. For the heating of 250 ml water, four types of glass beakers were used.

Table 1. Parameters of containers used at microwave heating tests

Type	Dimensions			Height of filling (mm)
	inner diameter (mm)	height (mm)	wall thickness (mm)	
Glass beakers				
B 1	87	94	1.5	42
B 2	49	150	2.5	132
B 3	59	110	1.5	92
B 4	66	92	1.5	74
B 5	59	78	1.5	62
Plastic trays, polypropylene, round				
T 1	120	47	0.4	30
T 2	180	23	0.4	13
Plastic trays, polypropylene, angular				
T 3, foamed PP	110 × 90	45	1.2	35.2
T 4, foamed PP (profiled bottom)	198 × 70	30	1.2	26
T 5	110 × 100	34	1.2	26

In the heating process, full power was adjusted on all microwave ovens. The respective glass vessel (beaker, tray) was put in the centre of the glass shelf (turntable) before heating.

In all measurements, the procedure according to IEC 705 standard was applied for the absorbed power estimation. The heating started at the water (solution) temperature $10 \pm 2^\circ\text{C}$. The time for the temperature of water (solution) elevation of $10 \pm 2^\circ\text{C}$ was measured. Before each temperature measurement, the water (solutions) was thoroughly stirred.

The microwave power absorbed in the fluid during its heating was calculated using Equation (1a).

For each parameter (oven, fluid, volume, container) the heating procedure was repeated 6 times and the mean value of the absorbed power and the standard deviation were calculated. A 30-min break was held between the individual measurements to avoid an excessive heating of the oven cavity.

RESULTS AND DISCUSSION

The decrease of the microwave power absorbed in the heated substance was found to be related to the decrease of its volume in all experiments in which the dependence between the load volume and the absorbed microwave power was followed.

The measurements carried out on four types of microwave ovens differing in the rated and calibrated power

output, cavity dimensions, placement of feeding input and cavity walls material confirmed that the ability of microwave oven to heat a small amount of a certain substance differs from oven to oven.

In Fig. 1, the relation is shown between the decrease of the relative value of the absorbed power (P_a/P_{\max}) and the decrease of the water volume for all four ovens tested (P_{\max} is the value of power found in heating of 1000 ml water).

Note: in this and other figures, the mean value of the power from six determinations for each test conditions is used. The exponential relationship proposed by Mudgett – with the volumetric coupling coefficient k as a part of the exponent – was used in the correlation (the least squares method was used). The values of k coefficient are given in the figure for individual curves. According to these results, the efficiency of heating of small amounts of water (smaller than 600 ml) was better in the small cavity ovens (Moulinex 650 W, Samsung 650 W) in comparison to the large-cavity ovens (Whirlpool 900 W, Moulinex 850 W).

The influence of certain other oven characteristics (technical parameters) on k value is evident from the comparison of the results obtained in the tests with the ovens of identical rated power and similar cavity volumes Moulinex 650 W and Samsung 650 W: k value of 15.6 (Moulinex 650 W) and 17.8 (Samsung 650 W). The better heating ability of Whirlpool 900 W in comparison to Moulinex 850 W – in spite of a little larger cavity volume – can be caused by both the different feeding system (dual feeding in Whirlpool) and the different cavity walls

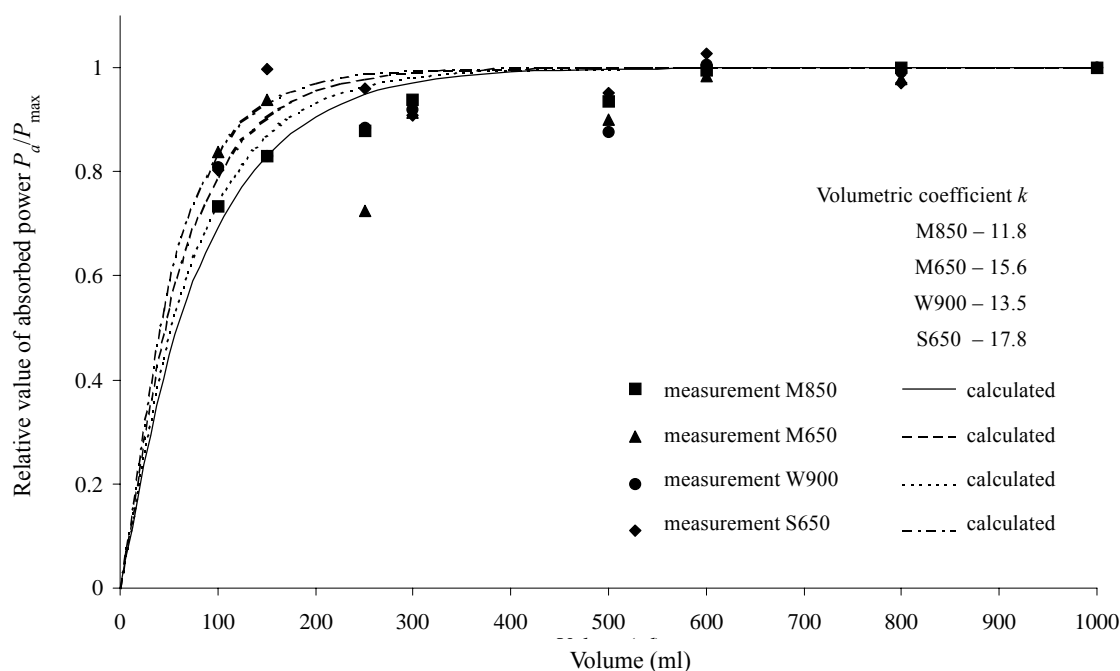


Fig. 1. Influence of the heated water volume on the absorbed microwave power (relative value) in a sample during microwave heating. Measured data and calculated curves according Equation (3). Tests with microwave ovens: Moulinex 850 W (M850), Moulinex 650 W (M650), Whirlpool 900 W (W900) and Samsung 650 W (S650). P_{\max} (calibrated value of power at heating of 1 l cold water) for M850 – 897.7 W, M650 – 674.2 W, W900 – 880.2 W, S650 – 684.7 W

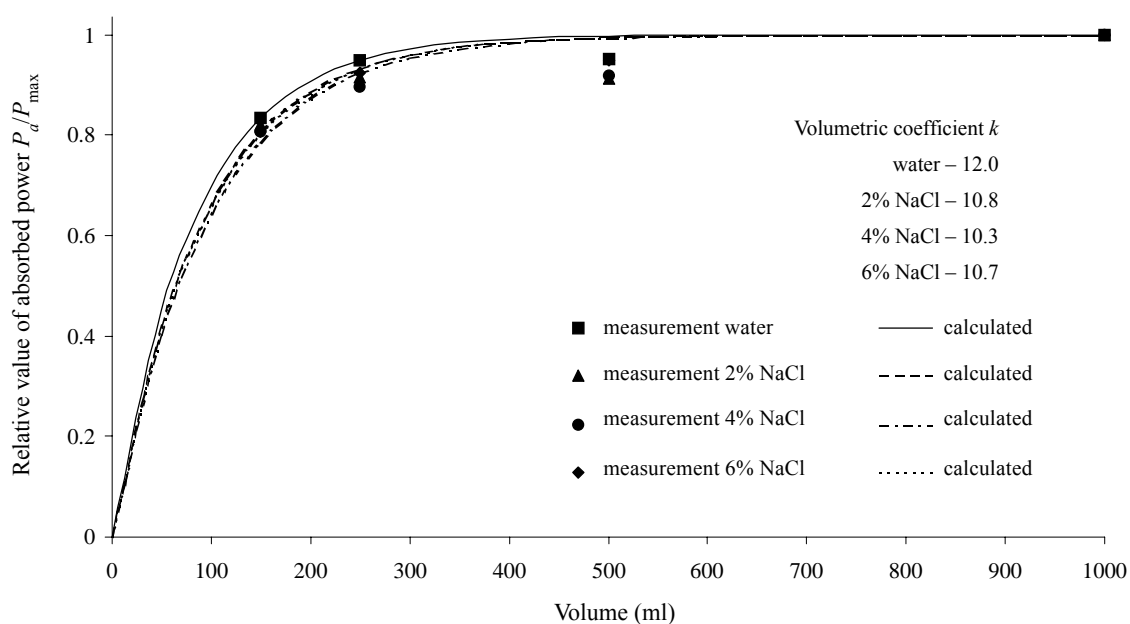


Fig. 2. Influence of the heated substance volume on the microwave power (relative value) absorbed in a sample during its heating. Measured data and calculated curves according Equation (3). Tests with water and NaCl solutions (2, 4, 6% concentration) heating in Moulinex 850 W oven. P_{\max} for water (1 l) 882.4 W, for 2% NaCl 902.2 W, 4% NaCl 890.5 W, 6% NaCl 883.5 W

material. According to BUFFLER (1992), the ovens with stainless-steel walls (in this case Whirlpool) have probably a better heating efficiency.

In the following two figures (Figs 2 and 3), the results are presented and compared of the experiments following the heating of different amounts of different fluids.

In all these tests, a microwave oven Moulinex 850 W and a glass vessel or glass beakers were used.

In Fig. 2, the rate of the relative value of the absorbed microwave power decreasing with the decrease of the heated sample volume is compared for the heating of water and NaCl solutions of 2, 4 and 6% concentrations.

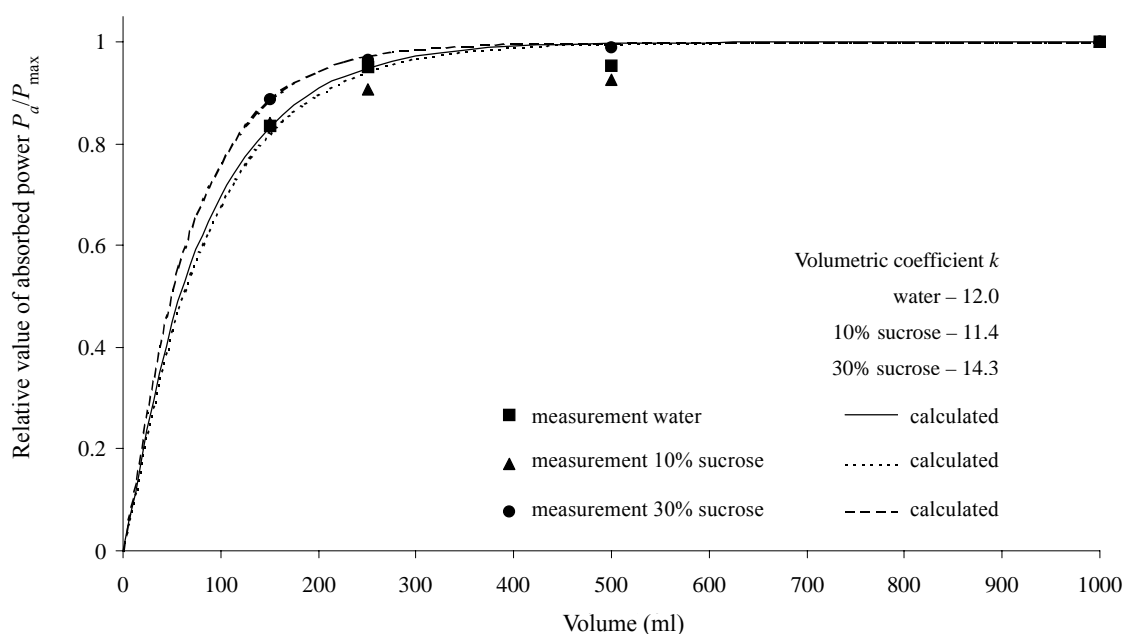


Fig. 3. Influence of the heated substance volume on the microwave power (relative value) absorbed in a sample during its heating. Measured data and calculated curves according Equation (3). Tests with water and sucrose solutions (10 and 30% concentrations), heating in Moulinex 850 W. P_{\max} for water (1 l) 882.4 W, 10% sucrose solution 881.7 W, 30% sucrose solution 822.3 W

In heating in the oven with the rated power of 850 W, the mean value of power absorbed in 1 l was 882.4 W, 902.2 W, 890.5 W and 883.5 W for water, 2% NaCl solution, 4% NaCl solution, and 6% NaCl solution, respectively. With respect to the standard deviations value (about $\pm 2\%$ of the relevant power value), these values can be considered practically as identical.

The comparison of the volumetric k coefficient values revealed small differences between the results with water and NaCl solutions heating: the value of k coefficient is about 12 for the water heating and about 10.8 for NaCl solutions heating. The influence of NaCl concentration in the solution on the value of k is small in the applied range of concentrations as follow from the results.

According to GRÜNEBERG (1994), the difference in the ability to absorb the microwave energy between small amounts of pure water and NaCl solutions can be explained by the differences in the dielectric properties. With the increasing concentration of NaCl solution, the dielectric losses (ϵ'') increase (affect the surface heating) and the dielectric constants (ϵ') decrease (affect the decrease in the energy dissipation). Depending on the concentration of the solution, the heating of small amounts of solutions can be the same (low concentrated solutions) or worse (high concentrated solutions, i.e. 10% and above) in comparison to the water heating.

The applied range of concentration in our experiments can be used for the explanation of relative small differences in the susceptibility of the tested samples of NaCl solutions to heating in the microwave oven.

The dependence between the volume of the heated sample and the absorbed microwave power for the heating of

water and sucrose solutions of two concentrations (10 and 30%) is presented in the Fig. 3.

Evident in this figure is namely the difference between the curve for 30% sucrose solution heating and two other curves (water and 10% sucrose solution). Values of the volumetric coefficient k : about 12 for water and 14 for 30% sucrose solution, respectively.

Also in this case, the differences in the dielectric properties of the heated substances can be used for the explanation of the results. Compared to water, the sucrose solution has a lower value of the dielectric constant ϵ' (about 59 for 30% sucrose solution and 76 for water, respectively – GRÜNEBERG 1994) and a higher value of the loss factor ϵ'' (25 for 30% solution and 14 for water, respectively) which affects the lower energy dissipation in sucrose samples and the surface heating. The susceptibility of a concentrated sucrose solution to heating by microwaves will be lower compared to the water sample. According to these tests, the microwave power absorbed in 1 l of water during the heating in the oven of the rated power output 850 W, was 882.4 W, and 822.3 W, respectively, in the case of 1 l 30% sucrose solution.

The standard deviations calculated for the estimation of the measurement accuracy for every mean power value were in most cases of tests about $\pm 2\%$ of the appropriate mean value of power. In the worst cases (heating of very small amounts of substances), the standard deviations rose to $\pm 5\%$ of the relevant mean value of power.

In Figs 4 and 5, the results are presented of experiments with the heating of certain amounts of water in containers of different parameters. (A certain influence of load/container geometry on the absorbed power is pre-

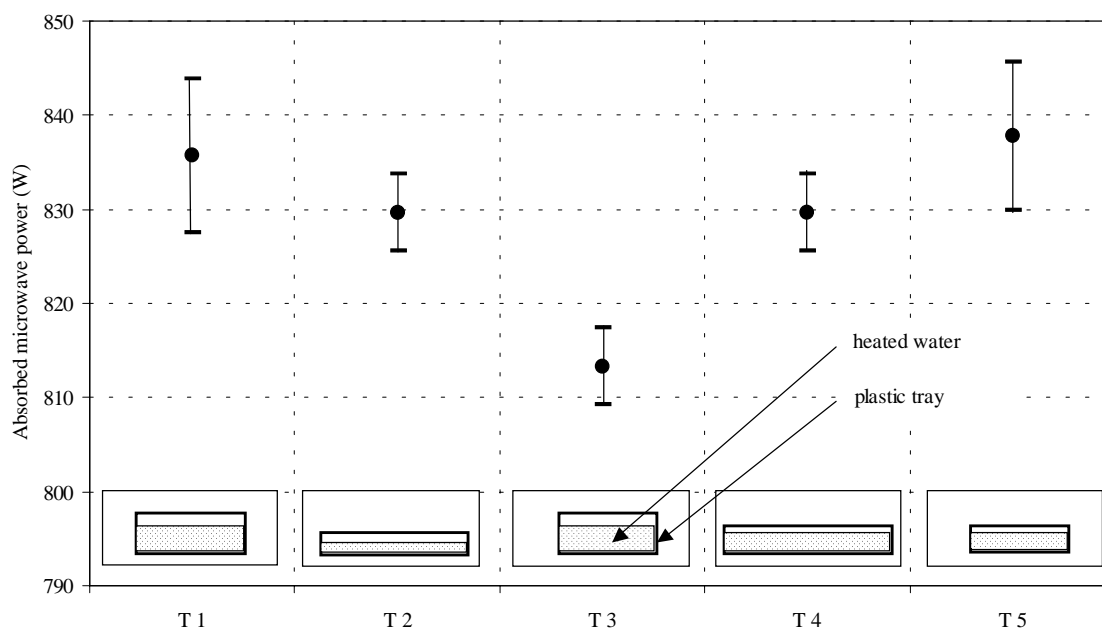


Fig. 4. Microwave power (mean, max, min values) absorbed in 350 ml water during heating in Moulinex 850 W. The influence of the plastic traytype (shape, material, dimension) was followed

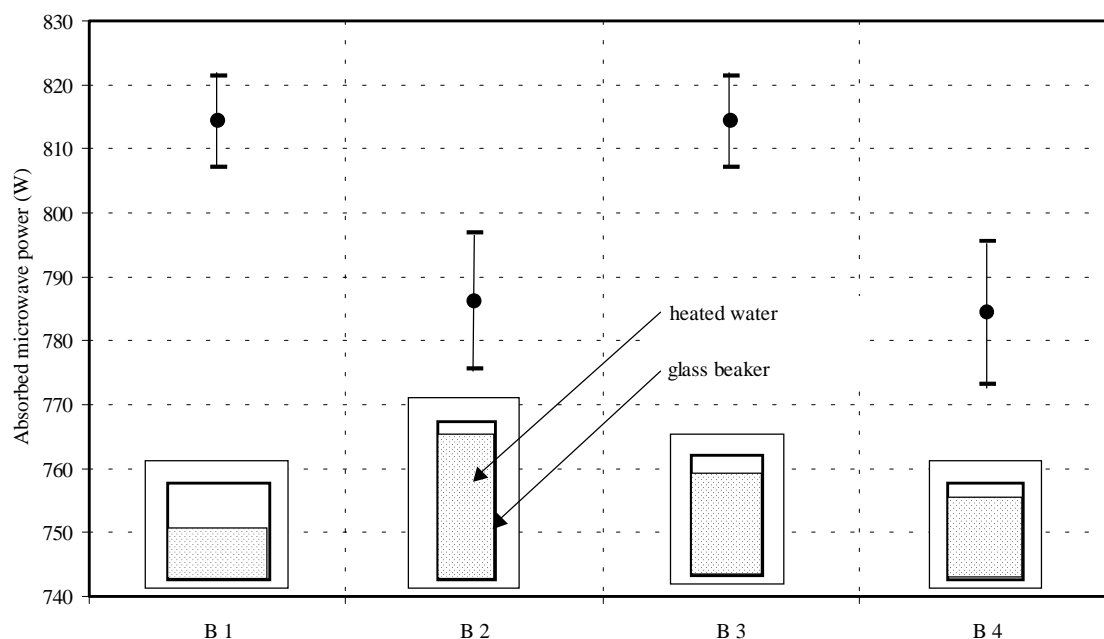


Fig. 5. Microwave power (mean, max, min values) absorbed in 250 ml water during heating in Moulinex 850 W. Four glass beakers of different dimensions were used in tests and the influence of the beaker type was followed

sumed by BUFFLER 1992.) In all these experiments, the microwave oven Moulinex 850 W was used.

In Fig. 4, the values of the absorbed power (mean values and power deviations in the replicate tests) in 350 ml of water heated in five types of plastics trays are compared. As can be seen, the geometry of the container had only a small influence on the amount of the power absorbed in heated water. The difference between the highest (tray T 3) and the lowest (tray T 2) mean values of the absorbed power represents only 3% of the highest value, which is the range of the measurement accuracy.

In Fig. 5, the absorbed power in 250 ml of water heated in four glass beakers of different dimensions is compared. (Except of the mean values also the maximum and minimum values of power in 6 replicate tests are given in the figure.) Also in this case, no simple dependence between the container dimensions and the microwave energy can be derived. The difference between the highest and the lowest mean values of power represents about 4% of the higher value. The same conclusion was found by GRÜNEBERG (1994).

Conclusions

1. The rated power output is a parameter used by microwave oven manufacturers in the labelling of ovens. International standard IEC 705 offers the parameters of the experimental procedure to obtain this parameter. This procedure has to be used in the power re-calibration.

2. A difference can exist between the rated power output and the power actually absorbed during the micro-

wave heating in the heated substance of certain parameters. Namely in the heating of small amounts of a substance, the volume absorption and therefore the efficiency of heating can be smaller compared to the heating of 1 l water as estimated according to the IEC standard.

3. The efficiency of small-volume-heating is oven-specific which complicates the prediction of the course of heating (time for the heating of certain product) in certain ovens.

4. Apart from the volume, the dielectric properties of the heated substances also influence the amount of the microwave power absorbed in the substance during its heating. In this paper, the efficiencies of the heating of water, NaCl solutions and 10 and 30% sucrose solutions are compared. The efficiency of low concentrated NaCl solutions (2, 4 and 6%) was comparable to that of the water heating, the sensitivity to the heated volume decrease was the same or a little higher. In the case of 30% sucrose solution heating, the efficiency of heating was lower compared to that of the water heating but the sensitivity to the decrease of the heated amount of solution was lower. Experiments with other fluids will be useful.

No simple dependence between the container geometry and the power absorbed in the heated substance can be derived from the tests results. Further experiments will be needed.

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Souhrn

HOUSOVÁ J., HOKE K. (2002): **Mikrovlnný ohřev – vliv zařízení a parametrů zátěže na absorbovaný výkon v ohřívaném materiálu.** Czech J. Food Sci., **20**: 117–124.

V práci jsme ověřovali míru závislosti skutečně využitého výkonu při mikrovlnném ohřevu tří druhů tekutin (voda, roztok NaCl a roztok sacharosy) na druhu a objemu tekutiny, na nádobě použité při ohřevu a na samotném mikrovlnném zařízení. K experimentům byly použity čtyři běžné typy mikrovlnných trub pro domácnosti se štičkovými výkony 650, 850 a 900 W a s objemem dutiny od 15 do 27 l. Testované vzorky měly objem od 150 do 1200 ml. K ohřevu byly použity skleněné nebo plastové nádoby různých tvarů i rozměrů. Absorbovaný výkon byl stanovován podle IEC 705 ze vzestupu teploty vzorku tekutiny během určité doby ohřevu při respektování fyzikálních vlastností tekutiny. Výsledky zkoušek potvrdily, že mezi výkonem mikrovlnného zařízení uváděným výrobcem a výkonem uplatněným při ohřevu určitého množství dané látky je značný rozdíl. Zkoušky ohřevu prokázaly, že při snižování množství testované tekutiny klesá efektivita ohřevu (vzrůst teploty v daném čase při stejné hodnotě nastaveného výkonu na zařízení je nižší), že míra tohoto poklesu je individuální s ohledem na zařízení a že v určité míře je ovlivněna i druhem ohřívané látky. Pro vyjádření závislosti mezi objemem ohřívané látky a poměrem skutečně využitého výkonu a výkonu zjištěného při ohřevu 1 l tekutiny byla použita exponenciální závislost, kterou navrhl MUDGETT (1988). Při hodnocení vlivu mikrovlnného zařízení jsme zjistili menší citlivost na efektivitu ohřevu u mikrovlnných zařízení s malým objemem dutiny (15, resp. 17 l) a nižším výkonem (650 W). Rozdíly ve výsledcích zkoušek provedených na mikrovlnných troubách se srovnatelným výkonem a objemem dutiny upozorňují na možný vliv i dalších konstrukčních parametrů zařízení, např. na pravděpodobně příznivý vliv nerezových stěn dutiny či dvouemisní systém u mikrovlnné trouby Whirlpool. Rozdíly v efektivitě ohřevu těchto objemů vody, různě koncentrovaných roztoků NaCl a zejména 30% roztoku sacharosy mohou být způsobeny rozdílnými dielektrickými vlastnostmi těchto látek. Zjištěné výsledky nejsou v rozporu s publikovanými poznatky (GRÜNEBERG 1994). Vliv geometrických parametrů nádoby (rozměry, tvar) použité při ohřevu stejného množství vody ve stejném zařízení na hodnotu absorbovaného výkonu nebyl jednoznačně prokázán. Zjištěné rozdíly se pohybují v rámci přesnosti měření pro příslušný objem tekutiny. Vzhledem k převážnému použití mikrovlnných trub k ohřevu relativně malých množství potravin je třeba při předpovědi průběhu mikrovlnného ohřevu respektovat možný pokles absorbovaného výkonu s poklesem množství ohřívané látky.

Klíčová slova: mikrovlnný ohřev; mikrovlnný výkon; absorpce výkonu

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