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Single Mode Circular Waveguide Applicator for Microwave Heating of Oblong Objects in Food Research

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Introduction

Microwave heating is well known for more than sixty years [1], [2]. Nowadays it is widely used in science and technologies for fast increasing of temperature of various objects and materials with significant dielectric dissipation factor. This method can be used for developing of new materials, e.g. sintering of ceramics [3]. But the widest field of applications of microwave heating remains in food industry for thawing, cooking, drying sterilization and pasteurization of various foods [4, 5]. A special application of microwave heating is very fast increase of temperature which is necessary for investigation of influence of food additives to the properties of final products. Rapid increase of temperature during 10-30 seconds can not be reached using conventional thermal methods.

The origins of heating are conducting losses and repolarisation of molecules in high frequency electromagnetic field. First of them predominates at lower frequencies up to tens MHz and the second one has maximal influence at frequencies from hundreds to thousands MHz. Most popular frequencies of microwave heating at the present moment are around 915 MHz and 2450 MHz. A repolarisation of water molecules at these frequencies causes significant losses of electromagnetic wave and increase of temperature.

A nature of microwaves allows concentration of them in small area. On the other hand, it is not easy to regulate this process, especially when heating of specific objects is required. A common shape of food products is oblong objects, such as sausage or fish fingers. They require concentration of microwaves along their axis.

Conventional microwave heating systems are designed to obtain uniform heat distribution [6, 7]. Power source is the magnetron which radiates energy into cavity of processing. Large volume of cavities with product or raw materials causes multimode electromagnetic field distribution due multiple scattering from walls. Therefore, a sophisticated pattern of standing waves with sharp peaks occurs in it. In order to obtain uniform heating, mode stirrers are used or processed material has to be moved in the cavity [2]. Multimode type of microwave heating is applicable when large amounts of product should be processed uniformly. However, required microwave power in this case can reach 10 kW [2].

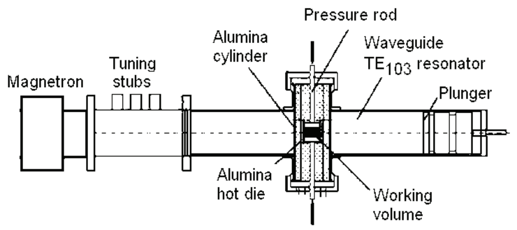
Relatively small samples of food material are used in development of new products. Therefore, uniform heating of large volume is not necessary but distribution of electromagnetic field must correspond to the size or shape of samples. A limited volume of heating allows use of single-mode cavity resonators and microwave energy could be more concentrated. This approach allows use of magnetrons with power less than 1 kW. Lower required power combined with simple design are the main reason of use of single-mode resonators.

Designs of single-mode cavity applicators

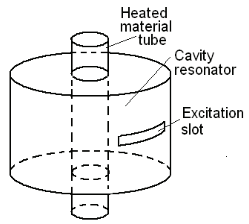
There are two main types of single-mode cavity resonators used in microwave heating applicators. The first one is based on rectangular waveguide where heated object is placed in maximum of electric field. Usually this place is formed using tube attached to wide wall of waveguide (Fig. 1-a) [8]. A resonator is formed by shorting one end of waveguide and tuning stubs are used to control resonant frequency and place of maximum of electric field. Wave mode TE_{103} is used in many cases of such resonators.

Another approach is a cylindrical cavity resonator with axisymmetric TM_{010} mode [9]. A dielectric tube for transportation of heated material is mounted through axis of this resonator. Microwaves are excited using magnetic loop or by slot in the wall of resonator (Fig. 1, b). Thus, this type of resonator requires additional transition from rectangular waveguide to excitation slot.

The main similarity of both types of resonators is the use of standing waves. The first type of design allows moving of standing wave by tuning plunger. The second one concentrates them in axial area.



a)



b)

Fig. 1. Single mode cavity resonators for oblong objects used for sintering of ceramics (a) and through-flowing material (b)

A main disadvantage of both types is that excitation of cavity is complicated and it requires additional tuning and matching elements, couplers and waveguide transitions. So there is a need for simple, effective and cheap microwave heating design.

Proposed design

In this paper we are presenting a new design of microwave heating device which uses axisymmetric TM_{01} mode in circular waveguide (Fig. 2). This mode allows concentration of electrical field in axis of waveguide. One end of waveguide is shorted and other is open so waves can be radiated outside. An excitation of TM_{01} mode is made using output pin of magnetron, which is placed in center of shorted end of waveguide. The open end causes partial wave reflection and standing wave peaks occurs in waveguide. On the other hand, part of energy is carried out by traveling wave and it aids more uniform heating of oblong food samples.

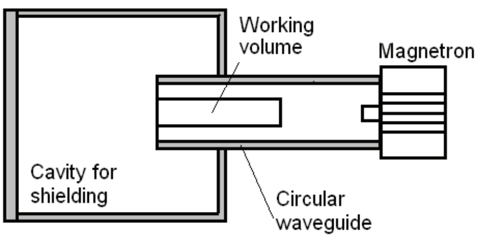


Fig. 2. Proposed applicator design of single-mode resonator based on open-end circular waveguide with TM_{01} mode

Electric and magnetic fields distribution of TM_{mn} mode in circular waveguide can be described using Bessel functions J_m of m^{th} order by analytical equations:

$$\begin{cases} \underline{E}_\rho = -j\dfrac{\gamma}{\gamma_p}\underline{E}_0 J'_m(\gamma_p\rho)\cos m\varphi, \\ \underline{E}_\varphi = j\dfrac{m\gamma}{\gamma_p^2\rho}\underline{E}_0 J_m(\gamma_p\rho)\sin m\varphi, \\ \underline{H}_\rho = -j\dfrac{m\gamma}{\gamma_p^2\rho Z_E}\underline{E}_0 J_m(\gamma_p\rho)\sin m\varphi, \\ \underline{H}_\varphi = -j\dfrac{\gamma}{\gamma_p Z_E}\underline{E}_0 J'_m(\gamma_p\rho)\cos m\varphi, \\ \underline{E}_z = \underline{E}_0 J'_m(\gamma_p\rho)\cos m\varphi, \end{cases} \qquad (1)$$

where ρ, φ, z are cylindrical coordinates; γ, γ_p – wave propagation coefficients along and across waveguide; Z_E is impedance of waveguide for TM mode.

A critical wavelength depends on radius of circular waveguide

$$\lambda_{kr} = \frac{2\pi}{\gamma_p} = \frac{2\pi R}{B_{mn}}, \qquad (2)$$

where $B_{mn} = \gamma_p R$ are n^{th} root of equation $J_m(\gamma_p R) = 0$. Mode TM_{01} has root B_{mn}= 2,405.

Length of heated zone and location of it depends on guided wavelength

$$\Lambda = \frac{\lambda}{\sqrt{1-\left(\lambda/\lambda_{kr}\right)^2}}. \qquad (3)$$

In order to obtain long enough volume of heating, peaks of standing wave in waveguide should be long as possible. Therefore, a used wavelength should be near to the critical value. It can be controlled by chose of radius of waveguide keeping in mind uncertainty of magnetron's frequency which can vary between 2400 and 2500 MHz (Fig. 3).

A circular waveguide with radius R=49 mm and length L=370 mm was chosen to use in applicator. This diameter allows operation near critical frequency which is 2347 MHz and guided wavelength is Λ=0,43 m.

However, this critical frequency will decrease when heated object will be placed in applicator. This effect is due the change of unguided wavelength λ when object with higher dielectric permittivity is placed inside of waveguide [10]. It is expected, that two maximums of electric field will exist in this waveguide.

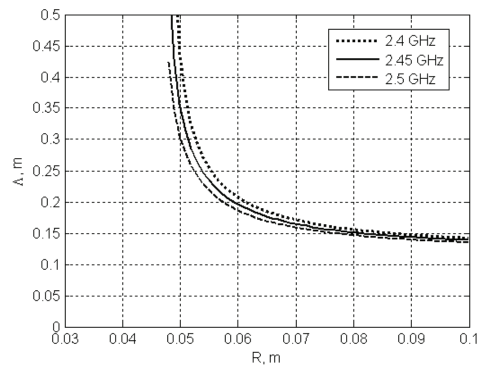


Fig. 3. Dependence of guided wavelength on radius of waveguide at certain frequencies of magnetron

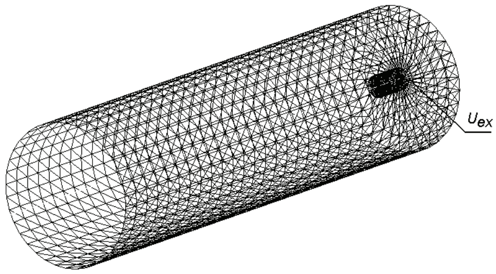


Fig. 4. Model of circular waveguide applicator. Excitation point is marked as U_{ex}

Results of simulations

More accurate analysis of microwave field distribution in waveguide was done using computational analysis. A computational model was build using high frequency structures analysis program FEKO. Model was based on conductive triangle elements (Fig. 4). It includes waveguide with shorted end and excitation pin of magnetron. An outer shielding and heated material was not included. It was assumed that frequency of magnetron is 2450 MHz ±50 MHz therefore simulation of field distribution in waveguide was performed at three frequencies. Power consumed by magnetron was 700 W. It was recalculated to excitation voltage U_{ex}=150 V assuming that radiation resistance magnetron pin is 30 Ω.

An efficiency of heating depends on value of electric field. Length of heated zone $\Delta L_{0.5}$ could be estimated using half-power level. Analysis of electrical field distribution shows, that there are two *E* field maximums in waveguide (Fig. 5). The first is near point of excitation and the second is near open end. The second one will be used for microwave heating. It is important to know not only $\Delta L_{0.5}$ but also diameter of this zone.

Diameter of heated object usually does not exceed 40 mm. It can be seen in Fig. 5, that electric field strength at 20 mm from axis exceeds this level so effective heating is possible in whole diameter of working area.

Another aspect of microwave applicator is exact place of field maximum. Analysis of equations (2) and (3) and corresponding curves in Fig. 3 shows that a small change in magnetrons frequency [11] causes significant change in guided wave length because of operating near critical frequency. Therefore, simulation was performed at three possible frequencies of magnetron.

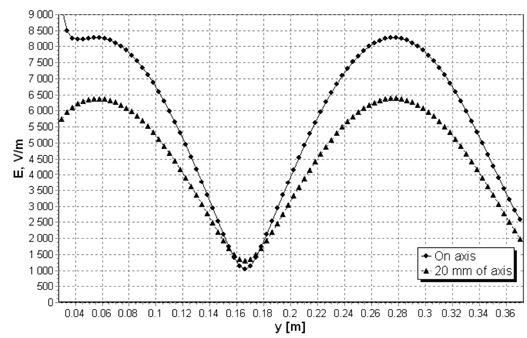


Fig. 5. Electric field distribution in open waveguide applicator along axis at 2450 MHz

A large variation in place of *E* field peak was found (Fig. 6). An excitation at 2400 MHz gives wide peak which is at distance 145 mm from open end of waveguide. Increase of frequency causes shortening of guided wave length and corresponding decrease of peaks' length as it can be seen in Fig. 6 and Table 1. Such significant variation of place and length of *E* field peak requires experimental proving of designed waveguide applicator.

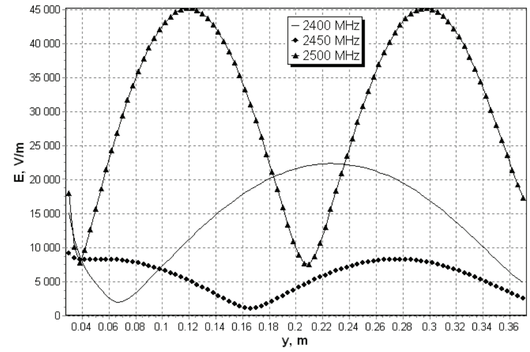


Fig. 6. Dependence of electric field distribution on frequency of magnetron

Experimental results

Field distribution in designed microwave heating applicator was proved using wet paper (carton). Microwaves have low loss in dry paper but in wet paper losses are significant and it causes burning of paper in peaks of electrical field. So, this method allows simple visualization of heated zones.

Width of carton sheet sample was equal to inner diameter of waveguide. One end of sample was aligned with the open end of waveguide. Duration of experiment was 20 seconds.

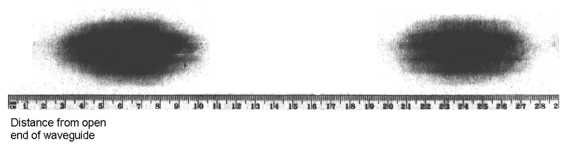


Fig. 7. Experimental validation of electric field peaks in waveguide using wet paper drying

It was found that there are two peaks of electric field as it was predicted by simulations. A distance between peaks is 180 mm and the second peak is located at distance 65 mm from open end of waveguide (Fig. 7, Table 1). Such guided wavelength corresponds to frequency of magnetron equal to 2492 MHz.

Table 1. Wavelengths of guided waves, places and lengths of heated zones

	Simulation at *f*, MHz			Experi-mental
	2400	2450	2500	
Λ, m	0,62	0,43	0,35	0,36
$\Delta L_{0.5}$, m	0,165	0,11	0,09	0,075*
Distance from open end, m	0,145	0,095	0,075	0,065

*Note: * Defined at border of burned zones*

Comparison of experimental and simulation results show that an acceptable agreement was found, especially in distance between peaks and location of second peak in waveguide. However, a change of dielectric properties of waveguide loaded by heated object was not included to model. Therefore, a small variation in position of peak could exist.

Conclusions

A new design of waveguide microwave heating device was proposed and developed. In contrast to other microwave applicators, our device doesn't require special tuning or excitation matching elements. Operating of waveguide applicator near critical frequency at TM_{01} mode allow expanding zone of microwave heating along axis of waveguide. Therefore, effective heating of oblong objects is possible by placing them in maximum of electrical field peak.

Analysis of peaks' length show that zone of effective heating is narrower than zone of half power. A rapid heating of samples in designed applicator is possible when their dimensions are approximately 40 mm x 70 mm. Expand of heated zone could be obtained using lower frequency. Moreover, proposed design of microwave applicator allows moving of standing wave peak along axis of waveguide using very small changes in frequency of operation. These changes can naturally occur during operation of magnetron due the heating and thermal expansion of device.

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A design of open waveguide resonator for microwave heating of oblong objects is presented in this study. This device is dedicated for research in food industry. In order to avoid misalignment of samples, an axis-symmetric wave mode TM_{01} is used in waveguide with circular cross-section. This approach allows rapid heating of oblong samples in axial area using relatively low power magnetron. In order to obtain longer zone of heating, an operating frequency was chosen to be near critical. Good agreement between simulated and experimental results was found. Ill. 7, bibl. 11, tabl. 1 (in English; abstracts in English and Lithuanian).

D. Kybartas, E. Ibenskis, R. Šurna. Pailgos formos objektų mikrobanginio kaitinimo įrenginys tyrimams atlikti maisto pramonėje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 8(114). – P. 79–82.

Pristatomas mikrobanginio kaitinimo įrenginys, naudojantis vienmodį apvalųjį bangolaidį. Šis įrenginys skirtas pailgiems objektams greitai įkaitinti maisto pramonėje. Įrenginyje panaudota ašiai simetriško lauko pasiskirstymo moda TM_{01}, kuri yra tinkama pasirinktojo tipo objektams šildyti, naudojant palyginti mažos galios magnetronus. Bangolaidis parinktas taip, kad jo darbo dažnis būtų artimas kritiniam, iš šitaip gauti gana ilgą fokusavimo zoną. Modeliavimo rezultatai gerai sutapo su eksperimentiniais. Il. 7, bibl. 11, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).