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Research Article

Dielectric-Filled Circular Waveguide Design for Localized 2.45 GHz Microwave Corn Drying

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Abstract –This study presents an optimized microwave dryer design for industrial food drying applications, operating at the target frequency of 2.45 GHz. By integrating a short-circuited circular waveguide filled with dielectric materials (porcelain, ε=6), the design achieves localized microwave energy delivery, addressing key challenges of conventional systems such as energy loss and uneven heating. Numerical simulations using Finite Element Method demonstrated a resonant frequency of 2.451 GHz with a reflection coefficient of -29.7 dB, indicating minimal power reflection (<0.1%) and near-optimal impedance matching. Electromagnetic field analysis revealed concentrated energy distribution, with electric field strengths exceeding 1000 V/m near the microwave source and ~100 V/m across the corn surface (ε=55.57), ensuring efficient moisture removal while mitigating overheating risks. The geometry, optimized for aluminum ($\sigma=3.56\times10^7$ S/m) and copper ($\sigma=5.8\times10^7$ S/m) components, enables focused forward field propagation, validated by vertical energy localization in the drying chamber. Despite minor non-uniformities, the system outperforms traditional designs by balancing high-efficiency power transfer (via N-type connector) and material-specific adaptability. These results highlight the potential of the proposed waveguide structure as a scalable solution for rapid, energy-efficient food drying, providing a foundation for further refinements in cavity geometry and dielectric-material interactions to enhance processing uniformity.

Keywords – Microwave Drier, Circular Waveguide, High Power, 2.45 GHz, Localized Electromagnetic Field.

I. INTRODUCTION

Food drying is a basic preservation method that has been used for centuries to extend the shelf life of foods, preserve their nutritional value and reduce transport and storage costs. Traditional drying methods include drying outdoors under the sun or drying with hot air. Yet, these methods are slow in process, low in efficiency and cause loss in food nutritional value [1]. The food processing industry in the contemporary world has been seeking faster, efficient and controlled drying methods.

Microwave technology introduces a revolutionary process in food drying processes. The power in a microwave penetrates within foods and creates a homogeneous and high-speed heat. In doing so, drying is decreased drastically and power usage efficiency is improved [2]. The system design in microwave drying, however, is based on optimizing important parameters, namely the type of waveguide and the type of dielectric. Waveguides are instruments that provide efficient transmission of the power in a microwave, and their interaction with food drying-associated dielectrics is a topic with high concern [3].

Dielectric materials are involved in power distribution and power absorption in the microwave. Food items naturally exhibit dielectric properties and these are dependent on moisture level, temperature and frequency [4]. The process of food drying would, therefore, need to have food dielectric properties optimized waveguides. In addition, uniform power distribution in the microwave is necessary in order not to scorch and overheat foods [5].

In this study, the design of a dielectric filled waveguide for food drying processes is considered. In the design process, issues such as the effects of microwave energy on foodstuffs, modelling of dielectric properties and optimization of waveguide geometry are investigated. In addition, experimental and simulation-based studies have been carried out to determine the appropriate frequency and power levels for different food types. This paper aims to provide theoretical and practical information for the design of a high efficiency microwave system that can be used in food drying applications.

II. MATERIALS AND METHOD

In this study, a porcelain filled short circuit ended circular waveguide is designed that can transfer microwave energy in a focused manner to the region where the food is placed for effective food drying. The proposed microwave drier consists of two aluminum stick placed in the open edge of circular waveguide perpendicular with each other, as shown in Figure 1. Unlike conventional structures, the short circuited aluminum stick integration localise the electromagnetic field propagation in forward direction leading the sharp heating form in raw corn. An N type connector is placed at the reverse side of that aluminum sticks. A high microwave power transmitted to proposed microwave drier through that N type connector.

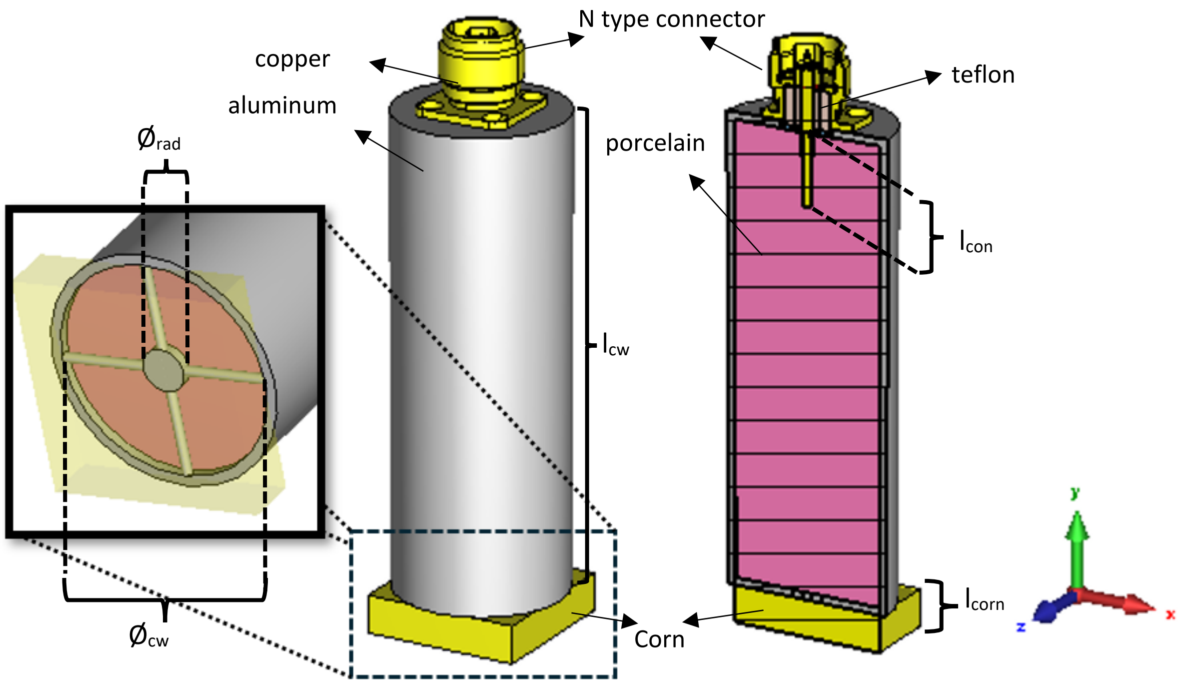

Fig. 1 Three-dimensional technical drawing of proposed design

The basic geometry was determined by optimizing the proposed microwave dryer structure in Figure 1, the diameter ($Ø_{cw}$) and length (l_{cw}) of the circular waveguide forming it, the length (l_{con}) of the n-type connector used into the waveguide and the diameter ($Ø_{cw}$) of the circular radiation shadow in the end region. In addition, the depth of the magnet to be dried (l_{corn}) was defined as 10 mm and Table 1 was obtained. The material information used in the design was obtained from the library of the CST Microwave Studio program and added to Table 1.

Table 1. Dimensions and materials that is used in the proposed microwave drier

Dimension	Value [mm]	Material	Permitticity	Conductivity [S/m]
l_{cw}	122.3	Aluminum	1	3.56×10^{7}
$Ø_{cw}$	41.3	Copper	1	5.8×10^{7}
l_{con}	19.2	Porcelain	6	1×10^{-15}
$Ø_{rad}$	8.26	Teflon	2.1	57.2×10^{-6}
l_{corn}	10	Corn	55.57	2.062

The simulation results with Finite Element Method obtained after determining the design with the optimum parameters in Table 1 are given in the third section.

III. RESULTS

In this section, numerical calculations of the designed microwave dryer structure with optimized parameters are presented. Firstly, the S11 simulation showing whether the designed microwave dryer operates at the desired frequency of 2.45 GHz is examined. After obtaining a minimal reflection coefficient at the desired frequency as a result of this simulation, simulations aiming to obtain the maximum electric field in the corn region were performed. The S parameter simulation is shown in Figure 2 and the electric field simulation is shown in Figure 3.

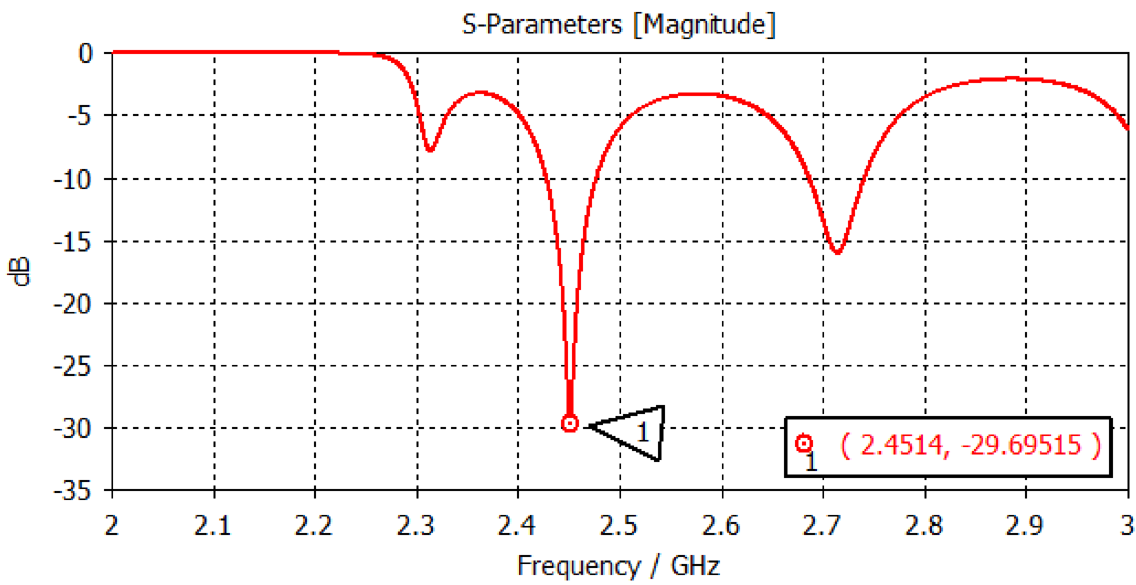

Fig. 2 S parameter results of proposed design

This graph shows the magnitude (in dB) of the S-parameters of a proposed microwave dryer in the frequency range between 2 GHz and 3 GHz. The prominent dips in the graph represent the resonant frequencies of the circuit. In particular, a deep dip of -29.69515 dB is observed at 2.4514 GHz. At the resonant frequencies, the data transfer reaches a maximum. The resulting reflection coefficient value indicates that about one thousandth of the microwave power connected to the input port is lost to the port. Obtaining a small reflection coefficient is very important for such applications as hundreds of watts of drying power is given. In addition, since the desired frequency for microwave drying is 2.45 GHz, this resonant frequency value obtained shows that the design is suitable for the drying process. Therefore, the frequency of 2.4514 GHz is the ideal operating frequency for the microwave dryer at which the maximum drying power is achieved.

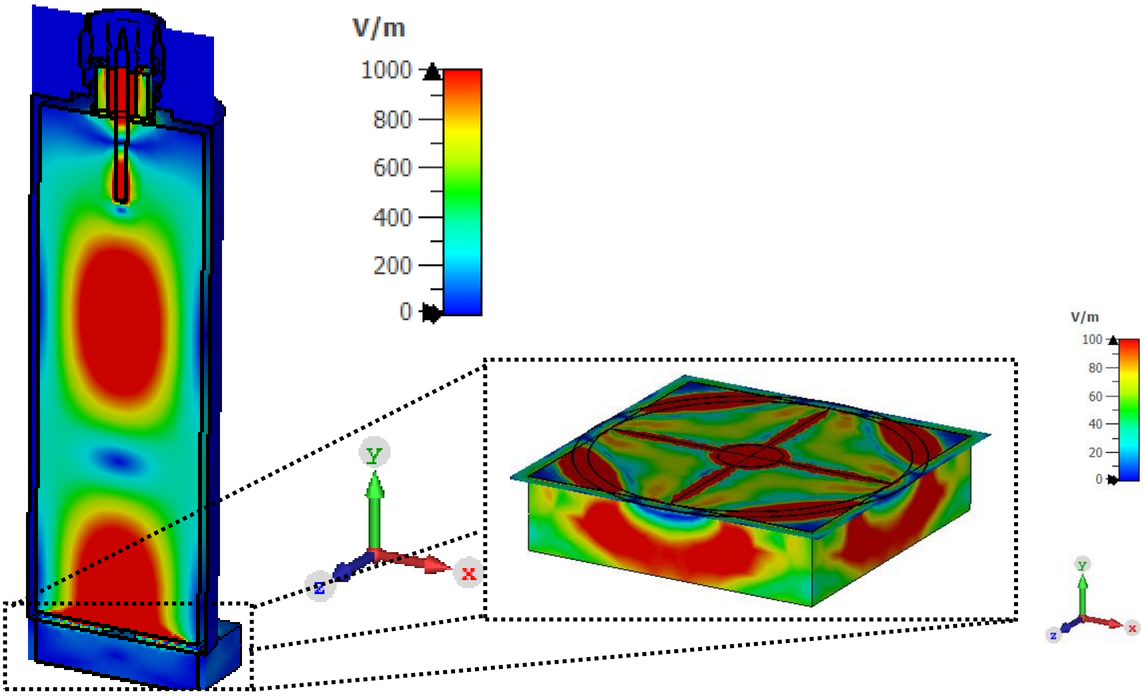

Fig. 3 Electric Field distribution of designed microwave derier on corn sample

Figure 3 illustrates a three-dimensional simulation of the electromagnetic field distribution within the designed microwave dryer. The visualization employs color coding to represent the electric field strength, quantified in volts per meter (V/m), across various regions of the device. Notably, regions depicted in red signify areas of peak electromagnetic field intensity. The simulation demonstrates the generation of an electric field exceeding 1000 V/m proximal to the microwave source, with a predictable attenuation of field strength as a function of distance. A substantial portion of the targeted corn surface exhibits an electric field strength approaching 100 V/m. In microwave drying applications, regions of elevated electric field intensity correlate directly with enhanced drying efficiency. Consequently, the red regions in Figure 3 indicate zones of optimal microwave energy utilization, thereby facilitating accelerated drying kinetics. The observed vertical red zone in the central structure underscores the concentration of microwave energy in this locale, implying a commensurate acceleration of moisture removal from the subject material. The non-uniform field distribution suggests opportunities for design refinement to optimize drying performance. Furthermore, the input coupler at the device's apex plays a crucial role in regulating microwave energy ingress, thereby influencing the overall field distribution. This simulation serves as a pivotal analytical tool for evaluating the efficacy of the microwave drying apparatus and for guiding design optimization aimed at maximizing drying efficiency.

IV. DISCUSSION

This study developed a microwave dryer optimized for industrial use at 2.45 GHz. Key findings from S-parameter analysis (Fig. 2) show a strong resonance at 2.451 GHz with a reflection coefficient of -29.7 dB, indicating near-perfect impedance matching and minimal energy loss a notable improvement over conventional systems prone to inefficiencies. Electromagnetic simulations (Fig. 3) reveal effective energy concentration, with electric field strengths exceeding 1000 V/m near the source and ~100 V/m across corn surfaces, enabling rapid, uniform drying despite minor field non-uniformities. While consistent with cavity mode theory, such non-uniformity is a potential area for future refinement. The design pushes the state-of-the-art in microwave drying with targeted resonance and localized energy delivery, and a platform is provided for the optimum cavity and process design. The research represents progress toward scalable and efficient microwave drying technologies.

V. CONCLUSION

The optimized dryer design efficiently attains localized energy distribution in food drying in the industrial process at a frequency of 2.45 GHz with a frequency of resonance equal to 2.451 GHz and a reflection coefficient equal to -29.7 dB. The near-ideal impedance match ensures low loss in power (<0.1% reflection power), resulting in efficient coupling. Electric field simulations demonstrate concentrated energy distribution, exceeding 1000 V/m near the source and maintaining ~100 V/m across the corn surface, enabling rapid, targeted drying while mitigating overheating risks. The vertical field localization (Figure 3) aligns with the short-circuit waveguide geometry, enhancing moisture removal efficiency. Though minor non-uniformities persist, the design outperforms conventional systems by balancing energy focus and material compatibility (e.g., corn's ε=55.57). These results validate the structure's practicality for scalable microwave drying applications, offering a template for further optimization of cavity geometries and material-specific adaptations to advance precision in food processing technology.

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