# 96 kW Industrial Hybrid Microwave Drying System Design


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***Abstract*—High power microwave drying systems offer great advantages in terms of power efficiency and processing. In the case of fresh fruits, microwave drying systems reduce the moisture content from 50-60% to 20-23%. When microwave drying process is coupled with hot-air injection into the chamber, the quality of the processed fruits is better than microwave only system. In this study, 96 kW hybrid microwave drying system operating at 2.45 GHz ISM band is designed for fig drying. To significantly lower the cost of the system, 1 kW magnetrons arranged in spatial orientation are utilized for each respective chamber of the system. Uniform heating over the running belt in this multimode applicator is targeted. The ends of the oven are open for loading and unloading of fig trays, which demands careful leakage suppressor design to satisfy 5mW/cm$^2$ field intensity outside the chamber. The whole system is designed, built, and validated with measurements.**



***Keywords*— high power microwave, fruit drying, magnetron, microwave applicator, fig drying**


## I. Introduction

Industrial microwave food drying systems have been studied extensively in the past [1-5]. Application of microwave drying to fresh fruits is particularly important as the time spent with conventional drying systems is much longer, which may lead to degradation in final product quality and growth of microbiological content that may eventually become toxic in time. To reduce the amount of microbial growth, certain chemicals must be used to avoid contamination. However, the amount of chemical use must also be in line with health regulations and standards which may easily become another issue in the process. Therefore, the whole drying process hinges upon two critical factors: the time spent from fruit collection from the field to the output of drying process, and the hygiene of the food containers and storage facilities to create mold-free environment. The hygiene of the containers and storage rooms can be controlled to some extent but prolonged drying time in a hot and humid environment creates perfect conditions for microbial growth. Thus, time spent for the drying system plays a crucial role for reliable and repeatable product quality. This requirement of process time may well translate into drying of fresh products in excess of 1000 kg in one hour, which may be demanding in terms of drying system design.

Hybrid hot air and microwave drying of fresh fruits offer several advantages over microwave only system [6-9]. Firstly, moisture removal is more rapid, and secondly, uniform heat distribution from outer skin to inner surface is more likely achieved. Besides, energy cost with hybrid system is usually smaller than microwave only system. Recent fruit drying application mostly focus on hybrid system due to the speed and energy efficiency of the whole process.

In this study, we propose large scale industrial microwave hybrid drying system to process figs. Application requirements and microwave drying system design are presented next.

## II. Requirements

The load capacity of the drying process in one hour and the required level of moisture removal from the product lead to the system specifications summarized in Table I. Moisture content of the target product is within 50-65% and the dried product is expected to be less than 23%. Lower than 20% moisture level may create conditions for caramelisation within the product. Also the outer skin stiffness and texture must be within product quality range. The microbiological toxins such as aflatoxin and ochratoxin A are regarded as the most common causes of degraded product quality and safety. Their reduction during the drying process could be also achieved to some extent but microbial analysis of the final dried products is not aimed in this study.

TABLE I. System level specifications

| Feature | Value |
|---|---|
| Mw Power | 96 kW (12 chambers w/ 16 kW each) |
| Conveyor belt speed | < 6 m/min (adjustable) |
| Hot air flow and suction speed | < 1000 m$^3$/hr (adjustable) |
| Hot air temperature | 50-55$^o$ C |
| EMC | CE compliance |
| Safety | < 5mW/cm$^2$ |

Overall system configuration is illustrated in Fig. 1, where 12 chambers each equipped with 16 kW of magnetron power and hot air module for air flow. To reduce system cost, the magnetrons compromise of 1 kW typical house-hold oven magnetrons with applicator and chamber specifically designed for optimum and homogenous field distribution. The magnetrons are Panasonic 2M244-M2 with +/- 10 MHz frequency deviation. However, from the batch of magnetrons, only +/-5 MHz deviation and with maximum 5% peak power deviation ones are selected. A special configuration with waveguide coupler is designed and water load is designed to test these parameters of each magnetron before being utilized in the system.

The mechanical and electrical control of the conveyor system is realized with Siemens PLC's (programmable logic control). The conveyor speed and magnetron duty cycles can be easily controlled with PLC.

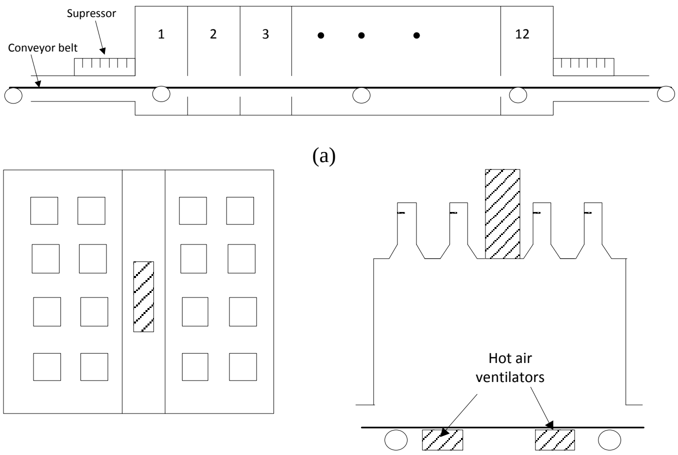

Fig. 1 System configuration, a) running belt and chambers, b) top view of a chamber, c) side view of a chamber.

## III. MICROWAVE SYSTEM DESIGN

The multimode microwave chamber is simulated with CST, Microwave Studio [10]. The waveguide applicator of each magnetron output is modeled and optimized for impedance match over at least 200 MHz centered at 2.45 GHz. The opening of waveguide to chamber is similar to standard gain horn with opening flares being optimized for energy coupling into the medium. Often the most difficult part of this interaction with the chamber is the impedance match under no-load condition. As the products are lossy, match under loaded chamber conditions is relatively easy to obtain.

The electric field distributions inside the chamber when the chamber is unloaded and loaded are shown in Fig. 2. The loading condition is simulated with figs laid in two-dimensional array configuration on the running belt plane. The shape of the fig is taken as two-spherically layered structure where outer shell represents the skin and inner sphere represents the high-moisture part of the fig. The electrical properties of these layers at 2.45 GHz were tested and verified at TUBITAK, Material Research Lab, Gebze, Turkey. As moisture is removed from the product, the electrical properties also change. This deviation in electrical characteristics is not measured simply because it is impractical.

Although simulations are carried out for coherent source, the practical implementation involves incoherent sources. Thus, the field representations provide only an indicative idea of overall system dimensions and expected field magnitudes.

Another critical aspect of any multimode magnetron oven is the uneven distribution of hot-cold spots on the applied product. This could be resolved either by rotating the product plane or using a mode stirrer. In present system, the conveyor belt runs at an adjustable speed where the speed can be controlled in tandem with magnetron duty cycle. Thus, the displacement of product from hot spot to cold spot can be controlled to maintain near uniform temperature variation on each product. Locations of hot spots are not periodic under loaded chamber condition due to scattered field from products.

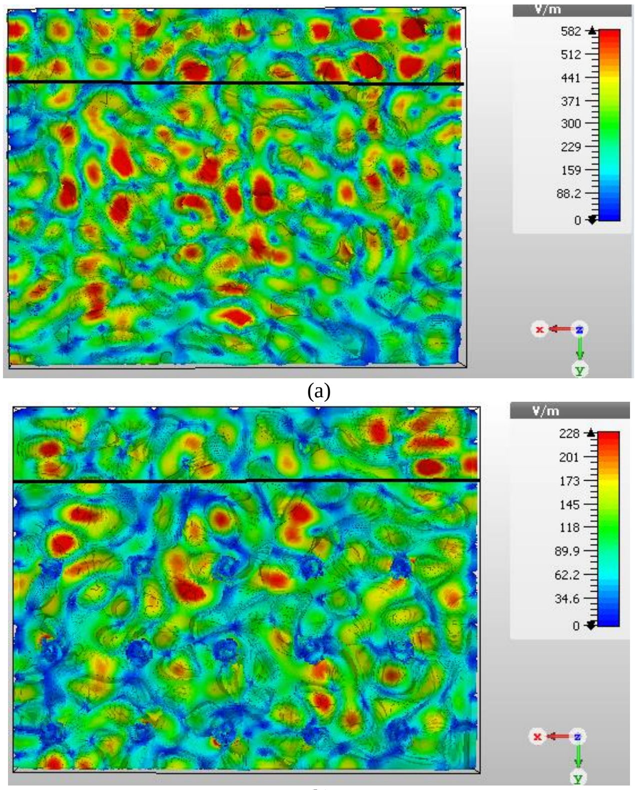

Fig. 2. Electric field distribution at product plane, a) unloaded, b) loaded.

Feed and guiding structure design plays a vital role for impedance match of each magnetron. Under unloaded and loaded conditions, the impedance matches of magnetrons are shown in Fig. 3. Magnetrons are spatially configured to minimize coupling to each other. When the chamber is loaded, this coupling is observed to be -20 dB or lower. Coupling under loaded and unloaded conditions are shown in Fig. 4 for ports 1 and 2 (one next to the other).

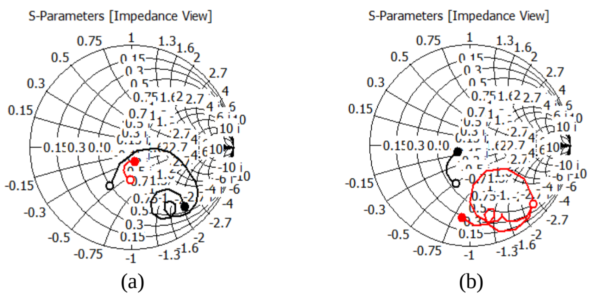

Fig. 3. Impedance match under unloaded and loaded conditions (2.445-2.455 GHz), a) port 2, b) port 4.

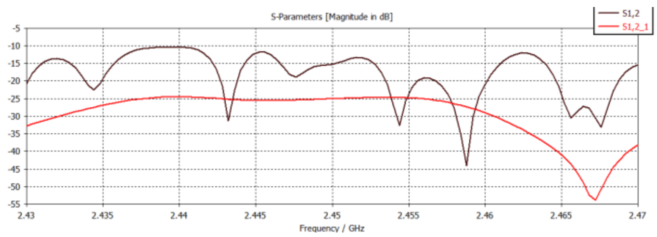

Fig. 4. Magnetron port 1 to port 1 coupling, unloaded (black), loaded (red).

Thermal simulations are also run to observe the temperature distribution and increase inside the fig. Simulation of one fig element is displayed in Fig. 5.

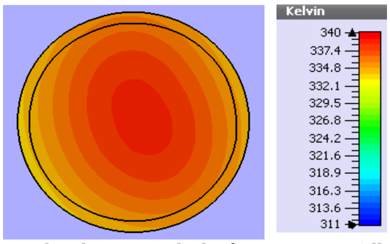

Fig. 5. Temperature distribution inside the fig at t= 12 ms (all magnetrons operating and To= 273 K).

The actual prototype of the system is shown in Fig. 6.


Fig. 6. Actual prototype of the system.

## IV. Conclusions

Hot air ventilated hybrid microwave drying system is designed and built for fig processing. The system achieves approximately 60 - 65$^{o}$ C temperature inside the fig and is capable of processing nearly 3000 kg of product per hour. The microwave chamber and applicator design are optimized for loaded and unloaded conditions. Especially when the chamber is unloaded, the reflected power back to magnetrons is assured to be within the safety margin of the chosen magnetron unit. Although not detailed in the manuscript, the water cooling of magnetrons are recycled to produce hot air used in the hybrid system. To satisfy EMC requirements and microwave safety, suppressors at the input and at the output of the open conveyor system are also designed, which are capable of more than 60 dB field suppression. The design and measurements results of the suppressor will also be presented at the meeting.

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