

Optimization of Microwave Vacuum Dryer Design Parameters using CST Microwave Studio for Low-Moisture Food Application

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Abstract—This study presents an optimized design of a microwave vacuum dryer (MVD) for rice bran stabilization addressing the problem with uneven heat distribution leading to scorching. Primarily, this study concentrates in further optimizing dimension of the chamber, orientation of the microwave generators, material volumes, and control system parameters. Using CST Microwave Studio simulation software, it is seen that the best design for a 30-L MV chamber operating at 2.45 GHz is a cylindrical chamber with a radius of 202mm, length of 400mm, and with 2 perpendicular feeders located near the ends of the chamber. For varying material volumes (50%, 70%, & 90%), the results show that overall, the 50% yielded the highest energy field, energy distribution, and absorption rate. However, all the models yielded results that are not very far from the other models. This means that the vacuum dryer design performs well at whatever level the material container is filled at. As for the control system of an MVD for rice bran, the parameters are soon to be established. Nevertheless, this study presents an overview of initial PLC schematic diagram that is partially tested for motor control which proved that parameters can be monitored and controlled.

Index Terms—CST Microwave Studio software, microwave vacuum dryer, programmable logic controller (PLC), rice bran

I. INTRODUCTION

RICE bran is a by-product obtained from milling brown rice to produce white rice. It has been found to be particularly rich in dietary fiber and contain significant amount of starch and protein and thus, regard as an

excellent additive for food and pharmaceutical applications. Approximately, 0.90 to 1.80 million metric tons of rice bran

was produced in the Philippines as a by-product of the 18.03 million metric tons rough rice output at a range of 5-10% rice bran [1]. Rice bran, which could be a potential source of human food, unfortunately, is still commonly used as animal feeds. The primary reason for the present failure of using rice bran for food purposes is the time lag between its production and utilization. To prevent the rice bran from becoming rancid, it must be subjected to stabilization process immediately after milling [2].

Drying is one of the oldest methods of preserving food. Conceptually, drying reduces the moisture in foods for two reasons: to inhibit the growth of bacteria and microorganisms (enzymes) and hence preserve the food and to reduce the weight and bulk of food for cheaper transport and more convenient storage. Though conventional dehydration processes including sun drying, solar drying, and freeze drying are widely used for food industries, they have disadvantages in terms of low drying rate leading to low energy efficiency and nutrient loss of finished product [3], [4]. These problems were considerably addressed in the development of a microwave vacuum drying (MVD) system. The combination of microwave heating and vacuum allows lower drying temperature and faster mass transfer resulting to a relatively higher quality of end product. In addition to that, the porous structure of microwave vacuum dried products often results in a shorter rehydration time, more complete rehydration, and higher water retention [5]. The microwave vacuum drying technology can be widely applied in the field of agro-products processing, especially suitable for heat sensitive materials that are prone to scorching such as rice bran.

Numerous attempts have been made to stabilize rice bran by chemical and thermal means. Stabilization can happen by lowering the pH of rice bran using hydrochloric acid [6]. But the most commonly used method of rice bran stabilization is the use of heat treatment which includes microwave heating inside a vacuum environment. Basically, a good design of an MVD must evenly dry rice bran and prevent it from scorching. So far, the effects of different dimensions of microwave vacuum chamber, the proper locations of microwave source, as well as the behavior of drying with varying material volume were not given much attention in the design optimization of an MVD. Therefore, the objective of this study was to bridge those considerations in a much optimized MVD. This was accompanied by a PLC-based controller equipped with human-machine interface (HMI) for monitoring and

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controlling system based on configuration software for microwave vacuum drying machine so as to improve the control performance and consequently reduce the operational cost.

II. MICROWAVE VACUUM DRYING SYSTEM

A. Components of a Microwave Vacuum Dryer

Microwave vacuum dryer is a modern technology of food drying. Through the use of microwave energy inside a vacuum environment, current problems taking place in conventional dryers and vacuum dryers such as long drying time and scorching are considerably addressed. A complete system diagram of a microwave vacuum dryer is depicted in Figure 1. The main components of the microwave vacuum dryer consists of 1) microwave vacuum chamber, 2) rotary drive assembly, 3) microwave applicator set (generating 0-1kW variable power), 4) ice condensing chamber assembly, 5) condensing unit, 6) vacuum pump, 7) pirani gauge, and 8) control panel box. Design materials needs to be considered especially for the attachments in the chamber that any protruded metal inside the chamber may be transformed into an antenna which may produce undesired plasma during drying process. Installation of a condensing unit (refrigeration system) may also be of an addition to prevent water accumulation in the vacuum pump that may damage, or to full extent, destroy the pump.

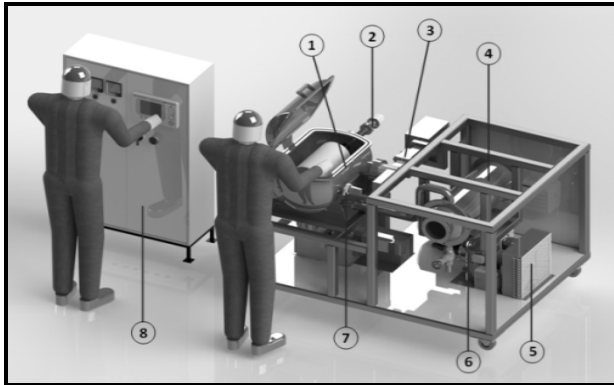


Fig. 1. Complete overview of a microwave vacuum dryer

B. Basics of Microwave Drying

The applied microwave energy will be transformed depending from the depth of vacuum directly into evaporation heat. If all the microwave energy is absorbed, the power density can be calculated using the following formula [7]:

$$P = 2 \cdot \pi \cdot f \cdot \epsilon_0 \cdot \epsilon'' \cdot E^2 \cdot V \quad \text{in } W/m^3 \quad (1)$$

Penetration depth of microwaves [7]

$$PD = \frac{\lambda_0}{2\pi} \cdot \frac{\sqrt{\epsilon''}}{\epsilon''} \quad \text{in } cm \quad (2)$$

where f is the frequency of microwaves, λ_0 is the vacuum wavelength, ϵ_0 is the electric field constant, ϵ' and ϵ'' are the real part and imaginary part of complex dielectric constant,

respectively, E refers to the electric field strength, and V is volume of material to be considered.

III. METHODOLOGY

Microwave simulations were performed using the software *CST Microwave Studio*. The system utilized microwaves with a frequency of 2.45 GHz, which is the same as what is used in conventional microwave ovens. Since there is no available material data for rice bran within the software, *wood* was instead chosen for the sample material in the model. For this study, the best chamber dimension was determined. Subsequently, the proper attachment of the microwave sources to the optimized chamber was evaluated. And lastly, the appropriate sample loads in the chamber for a more efficient drying was examined.

A. Optimization of Chamber Radius

In the study of radio frequency (RF) transmission, the VSWR (Voltage Standing Wave Ratio) is used as the measure of the efficiency of a transmitted RF signal. It can also be used to measure how well a load absorbs the incident microwave power, as well as how much power is reflected back to the source. Theoretically, the ideal value of the VSWR should be 1:1 or simply 1. This means that all the energy has been completely transmitted or absorbed and that there is zero reflection going back to the source. Conversely, an infinite value for the VSWR indicated complete reflection of the microwave power. Initial plan for the chamber radius was set at 175mm. For further optimization though, the VSWR of various chamber dimensions with a sample load was also observed.

B. Placement of Two Microwave Feeders

The model used for this simulation was the optimized chamber design. Six different orientations of two microwave feeders were simulated – 3 ports coplanar and 3 ports perpendicular. Figure 2 displays 3 possible designs for two perpendicularly-oriented feeders. Design A has both feeders along one plane near the end of the chamber. Design B has one feeder at the center while one feeder located near the end. Finally, design C has both feeders at both ends of the chamber.

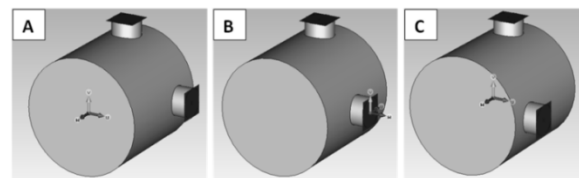


Fig. 2. Three perpendicular feeder placements for two microwave generators

C. Simulation and Optimization with Load

For the material sample, the model for the sample holder is filled with values of 50%, 70% and 90% of its maximum volume. The different volume levels can be seen in the model in Figure 3. The results that are monitored are: electric field intensity, electric energy density, specific absorption rate (power absorbed by the wood), and the S-parameters. In brief, the S-parameter is the ratio of the reflected microwave signal over the input signal in a

particular microwave port. Towards the goal of power optimization, the objective therefore is to have the S-parameter value as low as possible.

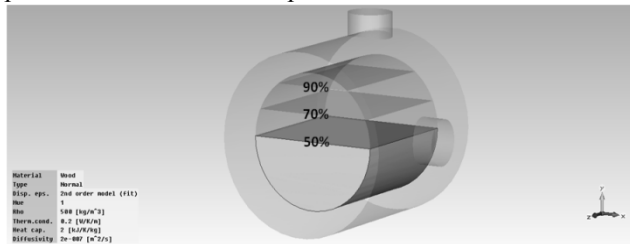


Fig. 3. Simulated percentage material volume

D. Control System Development

Basically, the whole system will be controlled by a Programmable Logic Controller or simply PLC. Every process will be activated accordingly as set in the programming of the controller. Figure 4 shows the block diagram of the control system for an MVD. The vacuum pump is the first one to be actuated. The pump is continuously operated until the end of the drying process. At the instant that the desired pressure is reached, the two magnetrons and the rotary motor will automatically start for the time duration set in the parameters setting. Vacuum pressure, microwave power, and temperature can be graphically monitored in the Human Machine Interface (HMI)

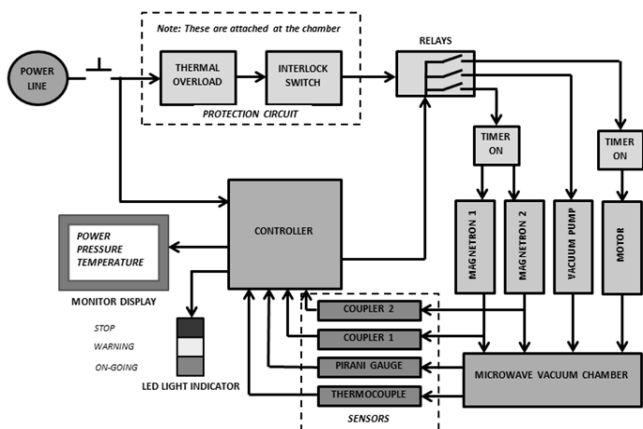


Fig. 4. System block diagram of an MVD

The principle of the PLC hardware system is shown in Figure 5. PLC used in the system is a Panasonic FP0-C16T with 8 digital I/O module to receive digit signals of the push buttons and overload protections, switch on vacuum pump, chiller (for cooling microwave applicator set), refrigeration system (for the protection of the vacuum pump), and control the stepper motor. There is also an extension module with an 8 analog I/O module provided to capture and measure signals such as the temperature and pressure inside the vacuum chamber, as well as the the incident and the reflected power of the microwave sources.

In consideration of the drying technology requirement of dried materials in the microwave vacuum drying machine, the drying processing parameters could be set optionally in the HMI such as the drying temperature, pressure level, microwave power, motor angular speed and drying time as depicted in Figure 6. As design optimization

is not a straight forward process, there will be an iterative characterizations and re-testing in order to meet the control parameters for rice bran.

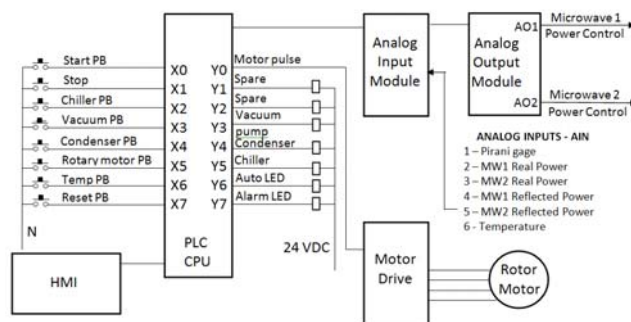


Fig. 5. PLC schematic diagram of the control system

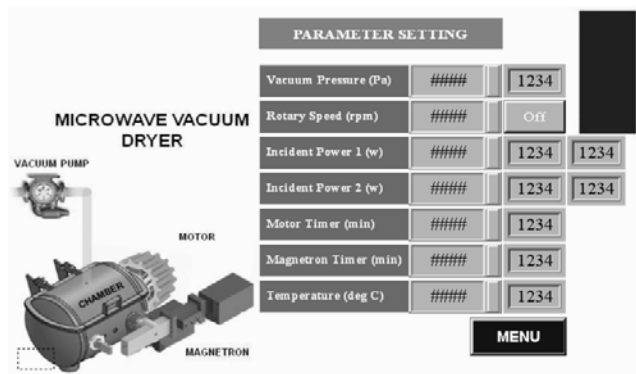


Fig. 6. Setting of drying parameters in the HMI of the control panel box

E. Control System Development

To study the drying characteristics of rice bran using microwave vacuum drying, the moisture ratio (MR) and drying rate (DR) of rice bran will be calculated using the following equations [8]:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

$$DR = \frac{M_t - M_e}{\Delta t} \quad (4)$$

where M_t is the moisture content (g of water/g of dry basis) at time t , M_e is the equilibrium moisture content (g of water/g of dry basis), M_0 is the initial moisture content (g of water/g of dry basis), which was assumed to be zero. $M_{t+\Delta t}$ is the moisture content (g of water/g of dry basis) at time $t+\Delta t$ and t is the time interval.

Proximate analysis of newly dried fine and very fine microwave-vacuum stabilized rice bran will be evaluated in terms of microbiological, sensory, physico-chemical, and functional properties. Microbiological analysis will be analyzed based on the Total Plate Count, Yeast and Mold and coliform as described in Bacteriological Analytical Manual (BAM). Physico-chemical analysis will include color, pH, water activity, phytic acid content and proximate composition namely crude protein, crude fat, crude fiber,

ash and free-fatty acid content. Functional properties will include bulk density, water absorption and fat absorption capacity, emulsification capacity and emulsifying stability, and foaming capacity and foam stability.

IV. RESULTS AND DISCUSSIONS

A. Optimized Chamber Dimension

The radius of the chamber was initially set at 175mm. However, when this dimension was simulated, the results shown in Figure 7.a reveal that there is a lack of energy near the axis of the cylinder, while most of the energy is distributed near the walls of the chamber and at the walls of the sample container. This may lead to problems with uneven heating especially at the center of the cylinder.

Attempting to improve the energy distribution, we increase the radius of the chamber by 20mm. Again the results are shown in Figure 7.b. One can see now that the energy distribution at the center of the chamber is improved, and “hotspots” along the length of the chamber are minimized.

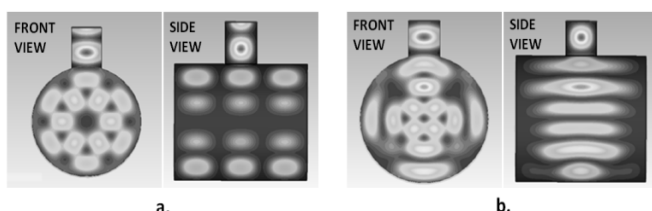


Fig. 7. Simulated energy distribution for a chamber radius of a) 175mm and b) 195mm

Figure 8 summarized the results for various chamber dimensions with a sample load and it is seen that the chamber radius is further optimized at 202mm, where the radius is 175mm + r and minimum VSWR can be found at $r = 27$.

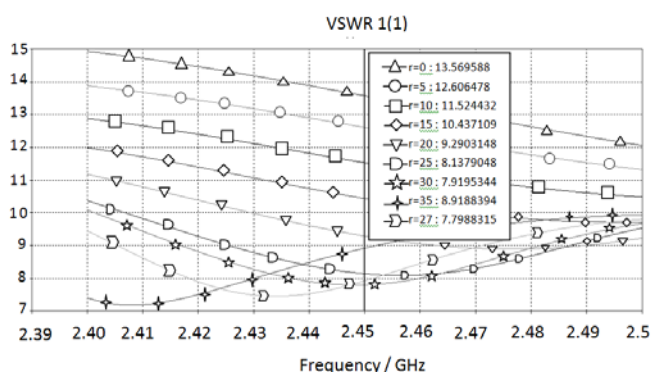


Fig. 8. Optimization of chamber radius by minimizing VSWR at 2.45GHz

B. Optimized Microwave Generator Location

Figure 9 shows the energy distribution for two microwave sources placed coplanar. It illustrates that all designs result to the energy being distributed near the walls. These are not ideal for the desired applications.

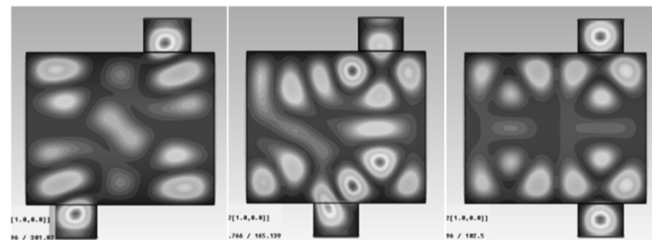


Fig. 9. Energy distribution for coplanar orientation of two microwave sources

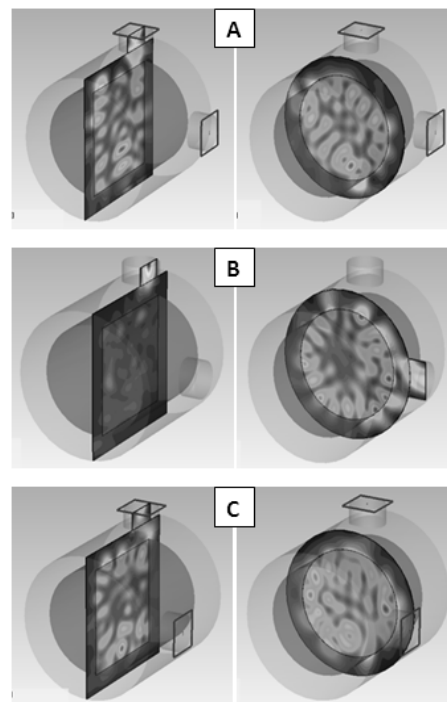


Fig. 10. Energy distribution for perpendicular orientation of two microwave sources

To see the energy distribution from the three different designs when the microwave sources are placed perpendicularly, paper was used as a material in the simulation to represent a material that has very low microwave absorption or a material that is nearly dry such as the rice bran powder. Figure 10 shows the different energy density results from the simulation. All designs yield a well distributed energy density. However, relatively, design C demonstrates a greater energy distribution both along the length and radius of the chamber. Moreover, design C also yields the highest efficiency of all albeit very small difference as summarized in Table 1.

Figure 11 shows a sample simulation of a microwave vacuum chamber design having 3 ports for microwave generator. This design actually improves the result for 2-port perpendicular attachment. However, it is the most expensive to build requiring three microwave sources.

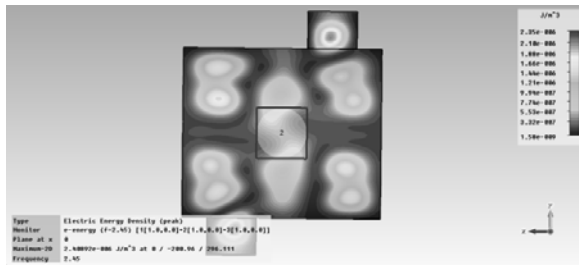
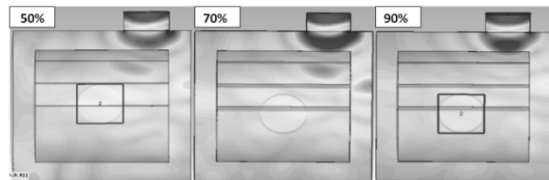


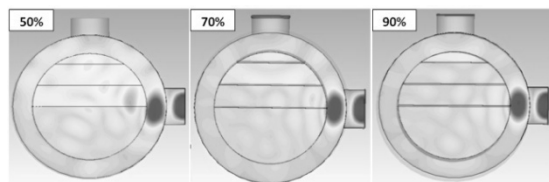
Fig. 11. Energy distribution for 3-port microwave source attachment to the microwave vacuum chamber

ELECTRIC FIELD INTENSITY

Side View

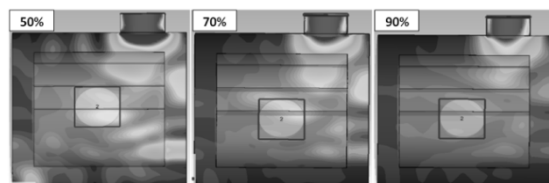


Front View

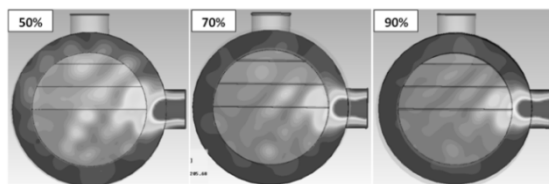


ELECTRIC FIELD ENERGY DENSITY

Side View

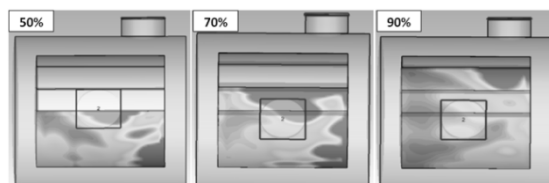


Front View



SPECIFIC ABSORPTION RATE

Side View



Front View

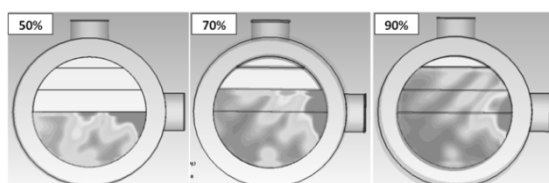


Fig. 12. Behavior of the electric field intensity, electric field energy density, specific absorption rate to varying load volume

TABLE I. PERCENTAGE ABSORBED POWER FOR THE THREE CONSIDERED LOCATION OF MICROWAVE SOURCES

Design	Percentage power absorbed
A	98.7211%
B	98.626%
C	99.0186%

TABLE II. POWER ABSORPTION PERCENTAGE FOR VARYING MATERIAL VOLUMES

Percentage Volume Filled	Percentage Power Absorbed
50%	96.9746%
70%	96.5519%
90%	96.554%

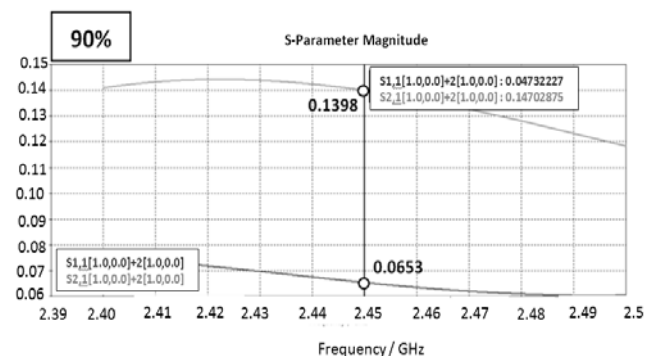
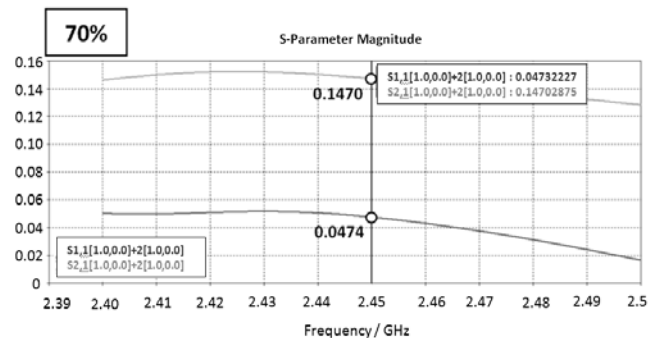
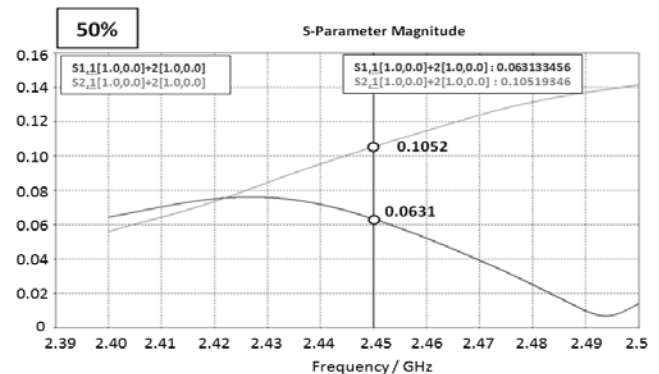


Fig. 13. S-parameter analysis for varying load volume

C. Optimized Material Volume

The effect of the material volume to the electric field intensity, electric field energy density, and specific absorption rate is shown in Figure 12. It can be seen from the results that the general pattern for the electric field remains the same in all cases. However, there is a slight difference in the magnitude of the fields between the three cases. The electric fields are generally higher when there is less material in the chamber because the microwaves are freely propagated in space. Similarly, for the electric energy

density, the distribution pattern remains the same among the different parameters. And again, a higher energy density is seen when there is less material. Overall, the energy is well distributed within the chamber in any of the conditions shown. For the absorption rate, the regions nearest the feeders have the highest value. This result necessitates the installation of a mechanism to rotate the material while in the drying process. Looking at the power absorption percentages, all values are very near each other. However, the highest value is found then the volume is at 50%. The reason maybe that this configuration has a better energy distribution and that much of the material is exposed the microwaves.

Looking at the S-parameters depicted in Figure 13, the 50% configuration generally gives the lowest values. This result supports the calculations on the power absorption. However, the values for the 70% and 90% models are not very far from that of 50%.

Considering the results of the simulations, an optimized design of an MV chamber was fabricated shown in Figure 14. The whole body is made of stainless steel type SS304 that is perfectly fit for food applications. Also, it has holes provision for flanges and for other component parts with proper sealing to ensure that no leakage in a chamber may occur.

Figure 15 illustrates a dry-run of the developed control system. The PLC was successfully interfaced with the stepper motor control, that is, if the speed of the motor is set at 40%, it rotates correspondingly and so on. Also, the temperature and pressure sensors were reacting as desired as it is monitored in the HMI displayed graphs.

V. CONCLUSION

Using CST Microwave Studio, simulations were done in order to optimize the dimensions of the chamber for microwave vacuum drying applications. In conclusion, the best design so far is a cylindrical chamber with a radius of 202mm, length of 400mm and with 2 perpendicular feeders located near the ends of the chamber. Simulations were also performed for varying material volumes. The electric field, energy distribution, absorbed power and S-parameters were investigated. The results show that overall, the 50% model yielded the highest absorption rate. However, all the models yielded results that are not very far from the other models. This means that the vacuum dryer design performs well at whatever level the material container is filled at. As per the development of the control system, parameters are soon to be determined but for the time being, it has been tested in a motor control that the PLC and HMI programming responded as desired.

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Fig. 14. Fabricated microwave vacuum chamber as the result of the simulations

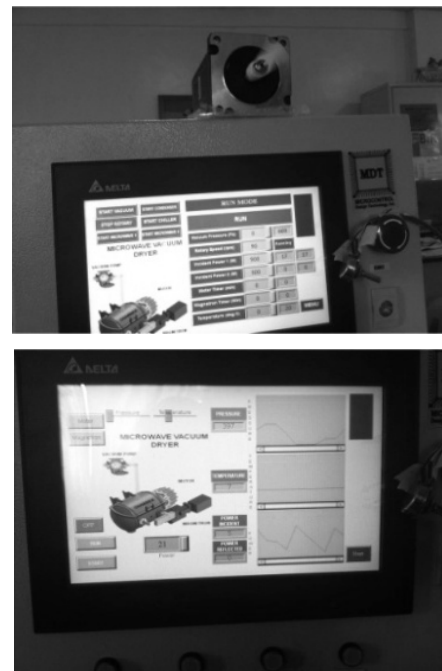


Fig. 15. Initial testing of the developed control system

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