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ANALYSIS OF THE EFFECTIVENESS OF METAL COVER IN PREVENTING RADIATION LEAKAGE IN MICROWAVE-BASED GASIFICATION REACTOR

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Abstract

Microwave-assisted gasification, which converts biomass and plastic waste into syngas, has significant promise for the production of clean renewable energy. This technology has the potential to reduce reliance on fossil fuels and address waste management challenges. Operational safety, particularly with microwave leakage, is a significant issue due to stringent standards for microwave exposure. This study evaluates the effectiveness of several metallic materials as microwave shields in microwave gasification reactors. This study investigates the effectiveness of 2 mm thick metal sheets made of copper, aluminum, iron, and stainless steel in reducing microwave leakage at a frequency of 2.45 GHz. Experimental results indicated that copper and aluminum are particularly effective shields. Copper attained a remarkable leakage reduction of 99.53% (from 105.6 W/m^2 to 0.5 W/m^2) while aluminum reached a decrease of 97.35% (from 105.6 W/m2 to 2.8 W/m2). Efficient reflection and absorption of microwave energy are facilitated by the extremely low skin depth values of both materials, which is consistent with their high effectiveness. However, iron and stainless steel also demonstrated a strong capacity to reduce leakage, with an efficacy of 89.96% (reducing leakage to 10.6 W/m2) and 73.86% (reducing leakage to 27.6 W/m2). Still, their performance was influenced by more complex magnetic properties. These results indicate that copper and aluminum are ideal choices for primary microwave shielding applications in gasification reactors. Conversely, iron and stainless steel, while less efficient as primary shields, offer excellent mechanical strength and corrosion resistance, making them suitable for auxiliary structural components. Therefore, a hybrid design integrating a thin shielding layer of copper or aluminum onto these structural elements is proposed for optimal microwave containment. This study provides crucial insights for the design of safer and more efficient microwave gasification reactors, thereby supporting the development of responsible renewable energy technologies.

Keywords: Microwave gasification, microwave leakage, shielding, skin depth, renewable energy.

I. INTRODUCTION

Gasification is a technology capable of converting biomass and plastic waste into synthetic gas (syngas)(1–3). In recent decades, gasification technology has developed rapidly. This technology offers the ability to produce cleaner and more environmentally friendly renewable energy while also potentially reducing reliance on fossil fuels and addressing the problem of waste accumulation(4–8). Various types of gasification reactors have been developed, ranging from coal gasification and combustion gasification to plasma gasification and microwave utilization.

The use of microwaves in gasification reactors has shown significant potential as a clean and efficient renewable energy technology(9–12). However, safety concerns related to microwave leakage are a crucial issue requiring effective solutions. Exposure to microwave radiation can pose health risks to operators and the surrounding environment(13), given that the maximum permissible exposure (MPE) for 2.45 GHz is 10 W/m2 as set forth in the IEEE C95.1 standard for industrial, scientific, and medical (ISM) applications(14,15).

Therefore, designing and implementing an effective safety system to prevent microwave leakage is highly important. One common method used in radiation safety systems is the use of shielding materials that can absorb or reflect microwaves.

This research aims to explore and analyze the application of covers made from metals, such as steel, aluminum, or stainless steel, as part of a microwave leakage safety system in microwave gasification reactors. This study will evaluate the effectiveness of these cover designs in reducing the level of microwave radiation leakage that may occur during the gasification process. A thorough understanding of the performance of these covers is expected to contribute significantly to the design of safer and more efficient microwave gasification reactors.

II. METHOD

A. Research Design

An initial investigation was conducted on a brand A microwave oven to evaluate microwave leakage in a microwave gasification reactor and to identify the most effective shielding material. Both the front and back sides of the oven exhibited leakage exceeding 5 mW/cm^2 The front side was chosen as the main focus for the next research. Figure 1 illustrates the designated locations for measuring leaks. The testing involved setting up a horn antenna connected to a SALUKI S5105D Vector Network Analyzer (VNA). Subsequently, we performed measurements in Spectrum Analyzer mode. Table 1 presents the initial data regarding microwave leakage.

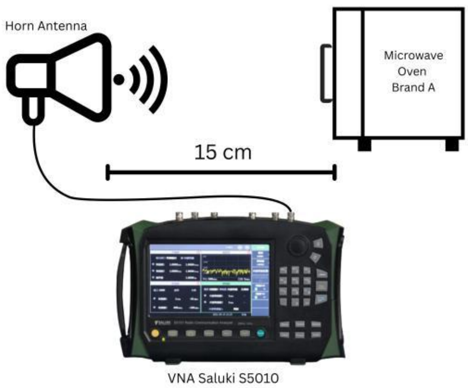

Figure 1. Measuring setup

Table 1. Data of Initial microwave leakage.

Side	Leakage W/m^2
Front (door)	105.6
Left	4.2
Right	0.8
Back	10.5
Top	0.2

The measurement data, initially obtained as field strength (dB\µV/m), was later converted into power density (W/m^2) using Equations 1 and 2(15):

$$\text{Power density } (W/m^2) = \frac{E^2}{377} \quad (1)$$

$$\text{Radiated Field Strength}(V/m) = 10^{\left(\frac{dB\mu V/m-120}{20}\right)} \quad (2)$$

The selected shielding materials were positioned in front of the microwave oven, and their leakage values were reassessed. Figure 2 illustrates the experimental setup after the shielding material was added.

Figure 2. Measuring setup with shielding material

The shielding material that efficiently blocked microwave leakage from the oven will serve as the cover for the microwave gasification reactor. This study looked at four types of 2 mm thick metal sheets: iron, aluminum, copper, and stainless steel. The findings revealed various levels of efficacy in preventing microwave leakage, with each material having unique features that influenced its shielding capabilities(16,17). Finally, the data will help to determine the best material for ensuring the microwave gasification reactor's safe and efficient operation. Subsequently, the data obtained from these measurements were used to calculate the effectiveness of the shielding material. The calculation was done by comparing the microwave leakage without the shielding material to the leakage observed after the shielding material was applied.

The fundamental concept of skin depth (δ) is employed to characterize the microwave shielding capacities of the researched materials. When an electromagnetic wave interacts with a conductive medium, the resultant currents and wave energy are localized on the surface of the substance(18). The energy intensity diminishes exponentially with increasing penetration depth(19). Skin depth (δ) is formally defined as the depth at which the electric field strength or current density attenuates to approximately 37% (1/e) of its surface value(20). It is calculated using the formula:

$$\delta = \frac{1}{\sqrt{\pi f \mu \rho}} \tag{3}$$

where:
ρ = material resistivity (Ohm-meter)
f = microwave frequency (Hertz)
μ = magnetic permeability of the material ($\mu_0 \times \mu_r$, where μ_0 is the permeability of free space and μ_r is the relative permeability)

The differences in how well materials block microwaves, depending on their electrical conductivity and magnetic permeability at the same microwave frequency(21,22), can be carefully studied and understood using this theory. A material with a reduced skin depth is significantly more efficient in attenuating and containing microwave radiation.

B. Operational Resarch Variabel

The study's dependent variables were the level of microwave leakage, quantified in W/m², and the resulting shielding effectiveness expressed as a percentage. The independent variable under investigation was the type of metallic shielding material used: copper, aluminum, iron, and stainless steel, all employed as 2 mm thick sheets. Control variables were rigorously maintained to ensure the integrity of the comparison. These included the constant microwave operating frequency of 2.45 GHz, the uniform thickness of the shielding materials at 2 mm, and the consistent measurement location at the oven's front (door) side at a fixed distance of 15 cm from the source.

C. Data Collection Teqnique

The data collection was performed through a series of experimental measurements conducted on a Brand A microwave oven. Microwave leakage was assessed by positioning a horn antenna 15 cm away from the oven and connecting it to a SALUKI S5105D Vector Network Analyzer (VNA), which was operated in the Spectrum Analyzer mode. Data acquisition was executed in two primary stages: first, to determine the initial leakage data without any protective material; and second, to record the leakage after the shielding material (copper, aluminum, iron, and stainless steel) was placed 3 cm in front of the oven. The raw field strength data, initially obtained in dB\μV/m,were subsequently converted into power density in W/m, using Equations 1 and 2.

D. Data Processing Teqnique

The collected data was subsequently processed through several steps. First, the raw field strength data was converted into power density W/m. Second, the measured leakage data were used to calculate the shielding effectiveness of each material. This calculation was performed by comparing the microwave leakage value without shielding 105.6W/m² to the leakage observed after the shielding material was applied. Finally, the resulting data were analyzed in depth using the fundamental concept of skin depth (δ). This concept of skin depth, which is calculated using Equation 3, is employed to characterize and understand the difference in shielding performance between materials based on their electrical and magnetic properties, where a material with a lower skin depth demonstrates greater efficiency in attenuating and containing microwave radiation.

III.RESULT AND DISCUSSION

A. Result

Microwave leakage tests were done on a brand A microwave oven in two different situations: first, without any protective material, and then with different 2 mm thick metal sheets (copper, aluminum, iron, and stainless steel) placed at the front of the oven (Figure 2). Preliminary data indicated a substantial leakage of 105.6 W/m2 from the oven's front (door) side. The complete measurements of leakage from various sides of the oven without any shielding, as well as the results after adding the shielding materials to the front, are shown in Table 2.

Table 2. Leakage measurement data (after the cover system is applied)

Material shielding	Leakage with W/m^2	Effectiveness (%)
Cooper	0.5	99,53
Aluminium	2.8	97.35
Iron	10,6	89.96
Stainless Stell	27.6	73.86

B. Discission

The experimental results clearly show significant variations in the microwave shielding effectiveness of the tested metallic materials. As presented in Table 1, the initial microwave leakage from the oven's front measured 105.6 W/m^2 This value substantially exceeds the maximum permissible exposure (MPE) standards for general public exposure (10 W/m^2) and even controlled/occupational exposure (81.7 W/m^2 at 2.45 GHz, thereby emphasizing the urgent need for effective shielding solutions. The concept of skin depth elucidates the mechanism of microwave shielding in conductive materials.

When an electromagnetic wave hits a conductor, the resulting currents and energy from the wave mainly gather close to the surface of the material, and their strength decreases quickly as they go deeper. A smaller skin depth for a given material at a specific frequency indicates a greater efficacy in reflecting or absorbing microwave energy, consequently minimizing penetration(17,18,23,24).

Copper exhibited superior performance, reducing leakage to just 0.5 W/m^2 and achieving an exceptional 99.53% shielding effectiveness. This remarkable performance is attributed to copper's extremely high electrical conductivity (very low resistivity) and its non-magnetic nature ($\mu r \approx 1$), which result in a very small skin depth (approximately 1.33 micrometers or 0.00133 mm at 2.4 GHz). Given that the copper sheet thickness (2 mm) significantly surpassed its skin depth, virtually all microwave energy was either reflected or absorbed within this very thin surface layer.

Aluminum also demonstrated highly effective attenuation, reducing leakage to 2.8 W/m^2 with an effectiveness of 97.35%.As a potent conductor, metal exhibits a minimal skin depth at 2.45 GHz, approximately 1.67 micrometers or 0.00167 mm. The 2 mm thick metal sheets effectively reflected and absorbed microwave energy.

Iron attained a significant decrease in leakage, from 105.6 W/m^2 to 10.6 W/m^2, yielding an efficacy of 89.96%. Although its attenuation was not as significant as that of copper or aluminum, this suggests that iron is a suitable shielding material. Iron exhibits complex behavior due to its ferromagnetic properties, enabling it to attract magnets and possess a significantly higher relative permeability ($\mu r>1$, typically ranging from 100 to over 5000, contingent upon the type and environment). Despite iron's minimal skin depth of around one millimeter at 2.45 GHz, its pronounced magnetic characteristics might induce additional energy losses through hysteresis and eddy currents, potentially leading to diminished reflection efficiency or resonance complications. The achieved effectiveness of 89.96% indicates that iron's conductivity at this frequency is still the most significant factor in microwave reduction, although it may be constrained by complex magnetic interactions that prevent it from reaching the highest performance levels of non-magnetic conductors.

Stainless steel also exhibited positive shielding effectiveness, reducing leakage to 27.6 W/m^2, with an effectiveness of 73.86%. While this represented the lowest effectiveness among the tested materials, stainless steel nonetheless significantly lowered the leakage from the dangerously high initial levels. Stainless steel's complex alloy composition and magnetic properties (varying by type, such as non-magnetic austenitic versus magnetic ferritic/martensitic) influence its shielding characteristics. For magnetic stainless steel types, the skin depth at 2.45 GHz is also very small. However, the way its conductivity and magnetic permeability work together in the alloy might make it less effective at absorbing or transmitting energy compared to iron, or it may not have the best balance of conductivity and permeability for microwave shielding at this frequency.

Microwave gasification reactors represent a promising method for generating pure, renewable energy through the conversion of biomass or plastic waste into syngas. Given that these reactors utilize high-power microwaves, it is essential to preserve the integrity of the microwave containment system to safeguard both the environment and operators. The experimental findings and theoretical comprehension of skin depth underscore the vital importance of selecting shielding materials judiciously. Copper, with an efficacy of 99.53%, is the preferred material for constructing covers for microwave gasification reactors, especially in regions requiring optimal protection. Its exceptional attenuation capability, supported by a substantial skin depth, guarantees low microwave penetration. Aluminum, which has an efficiency of 97.35%, is another very competitive material. This material is an excellent combination of lightweight, effective radiation suppression, and lower cost than copper. Additionally, the ease of production of aluminum is a significant advantage. This makes it an excellent choice for reactor designs that want to keep costs down while still being economical to build. However, while iron and stainless steel aren't quite as effective as copper or aluminum at blocking microwaves (showing 89.96% and 73.86% effectiveness, respectively), they still do a significant job in bringing down dangerously high initial radiation levels. The big advantage of these materials is their exceptional strength and resistance to corrosion, making them perfect for the structural parts of reactors that need to hold up in really tough conditions. Iron is also the cheapest and easiest material to work with. A hybrid material approach can be used for designing microwave gasification reactors. For example, a strong structural core made of iron or stainless steel could be lined with a thin layer of copper or aluminum on the inside or outside to provide the best microwave shielding. This method lets you get the most out of reactor safety and durability at the same time while keeping costs and production possible.

Ultimately, the design of microwave gasification reactors that are both safe and efficient should prioritize the use of cover materials that are recognized for their ability to effectively reduce microwave leakage and are compatible with the optimal thickness required for shielding. Also, practical aspects like the cost of the materials, how easy they are to make, and how well they can stand up to the reactor's working environment (such corrosion and chemical exposure) need to be looked at in depth.

IV.CONCLUSION AND SUGGESTION

A. Conclusion

This research presents a comprehensive evaluation of the efficacy of various metallic materials, including copper, aluminum, iron, and stainless steel, as microwave shields at 2.45 GHz. This research is directly pertinent to the safe operation of microwave gasification reactors. Our results clearly show that copper and aluminum are excellent at blocking things. They reduced leakage by 99.53% and 97.35%, respectively. Their modest skin depths, which facilitate the reflection and absorption of microwave energy, align with their superior performance.

Despite their reduced but still significant shielding capacities (89.96% and 73.86% efficacy), the complex magnetic characteristics of iron and stainless steel influence their performance. These materials are forceful and resistant to corrosion, which makes them perfect for structural parts in hostile reactor conditions.

Because they have been shown to work quite well, copper and aluminum are highly suggested for primary shielding in the construction of microwave gasification reactors. Iron or stainless steel can be used wisely for structural parts. A thin layer of copper or aluminum can also be added to make a hybrid system that enhances both structural integrity and microwave containment. This method takes into account practical things like the cost of materials and how easy they are to make while also making sure that safety and durability are as high as possible. Our research gives important information that will help make microwave gasification technology safer and more efficient. This will help renewable energy grow in a responsible way.

B. Suggestion

Further research is recommended to expand the study's scope to optimize the design of safe and efficient microwave gasification reactors1. A crucial step is to conduct an in-depth study on hybrid shielding designs. This design should integrate structurally robust materials like iron or stainless steel—which excel in mechanical strength and corrosion resistance—with a thin lining of high-performance primary shielding material, specifically copper or aluminum, to ensure optimal microwave containment Furthermore, it is essential to investigate the effect of varying thicknesses of the shielding materials, particularly for copper and aluminum, to identify the most cost-effective thickness that still meets safety standards5. The research should also include a more detailed analysis of the shielding behavior of iron and stainless steel, specifically considering how their complex magnetic properties (μ_r> 1) influence attenuation and potential sources of additional energy loss. Finally, a comprehensive study needs to be developed to evaluate not only the shielding performance but also the practical and economic aspects such as material cost, ease of fabrication, and the material's compatibility with the corrosive or chemically exposed environment of the gasification reactor

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