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SCALABLE MICROWAVE WASTE-TO-FUEL CONVERSION

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Introduction

This paper presents an efficiency study for scalable microwave waste management. When waste with carbon content is subjected to volume power densities on the order of 0.25W/cm^3 at GHz frequencies, it converts to solid coke fuel with oil and gas bi-products that can further be for fuel, leaving no trace. For an efficient process, a well-controlled uniform RF field should be maintained in a non-uniform and time-variable material. We are developing a 2.45-GHz active microwave cavity with solid-state (GaN) spatially power combined sources for lower volumes, Fig.1. In the energy balance calculations, the input energy into the system consists of the waste chemical energy and the DC electrical energy used to obtain the RF power with an efficiency that can reach 70% for kW power levels. The efficiency of RF power conversion to heating rate in the waste mass is calculated from full-wave simulations for four waste mixtures, input power, and operating temperature. The output energy estimates are collected from various pyrolysis process descriptions, e.g. [1], with the total energy being that of the solid fuel (35MJ/kg) and oil caloric values, e.g. 40MJ/kg for plastics and about 10-15MJ/kg for non-plastics [2]. A byproduct is flue gas, which can be converted to synthetic gas fuel (Syngas) as described in, e.g. [3].

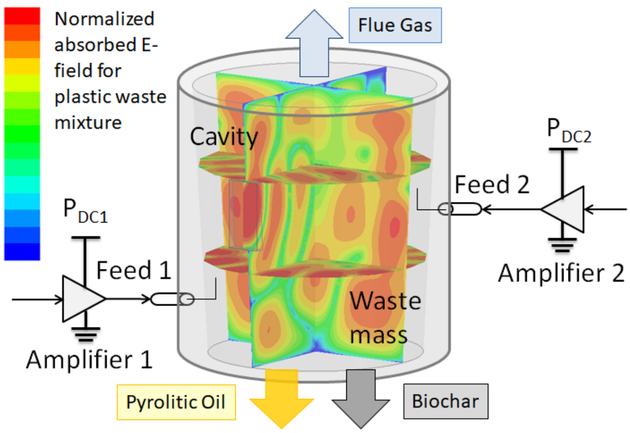

Fig. 1. Block diagram of an active microwave cavity for waste to fuel conversion. The cavity is fed by several power amplifiers with probe outputs. Absorption of microwave energy results in waste conversion into solid fuel (biochar), oil which can be converted to liquid fuel, and flue gas which can be converted to synthetic gas fuel. The relative phase between the feeds, mass mixing, frequency modulation and mode mixing can be used to ensure high uniformity of the electric field within the waste mass.

DC to RF Conversion
The two methods to obtain kW-level power at GHz frequencies are solid-state power amplifiers and tubes. In the 2GHz range, GaN transistors have demonstrated high power levels with high efficiency, e.g. [4],[5] and can be further power combined. Magnetrons have also been power combined with power combining efficiencies above 90% to achieve power levels around 30kW [6]. The analysis in this paper is not specific to a particular type of RF power generation, and is described by a conversion efficiency which is assumed to be 70%.

Electric Field Simulations
The fields inside the waste volume produce heat through Joule losses. The thermal power produced in the cavity depends on the filling material properties, relative permittivity (ε_r), conductivity (σ), geometry of cavity and type of excitation, and is calculated from:

$$P_{Th} = \iiint |E(x,y,z)|^2 \sigma(x,y,z) dV \tag{1}$$

It is desirable to keep the power density of Joule losses uniform through the heating process, because that usually results in the best time-average efficiency. This analysis was done using a single waveguide port excitation. There is a tradeoff between large volumes which can have a high level of field uniformity and small volumes which are effectively heated with a single feed. Several rectangular and cylindrical cavities, with volumes ranging from 0.0008m^3 to 0.15m^3, were compared using a full-wave eigen-mode solver (Ansys HFSS) to determine the modal content around the operating frequency of 2.45 GHz. The chosen cavity has the shape of an actual trash-can, cylindrical in shape and with one base larger, Fig.2. For the simulations, the radii of the bases are chosen to be R_1 =12.7cm and R_2 =11.2cm, with a height of H =28.2cm. The feed is an S-band (WR340) waveguide port with a lower edge 13cm above the bottom of the cavity. A larger version of this system will include multiple waveguide ports that are strategically placed to uniformly excite the waste volume under varying permittivity and loss conditions.

Equation (1) can be simplified if the waste volume is assumed to consist of sub-volumes that have uniform conductivities, where the integral becomes a sum:

$$P_{Th} = \sum_{k=0}^{n} \sigma |E(x,y,z)|^2 \Delta V \tag{2}$$

The fields can be found using a full-wave EM solver, given a specific geometry, electrical properties, and excitation. Plots of the magnitude of the electric field throughout the cavity are shown for two extremes of the four cases in Fig. 2. The breakdown of the food mixture was not detailed in reference [8] and for this analysis a mixture of 45% meats and starches, 35% fruits and vegetables, and 20% fats was assumed. This food mixture, high permittivity and loss, shows absorption near the feed and would improve with multiple excitations. Whereas the low-density polyethylene, LDPE, and polystyrene mixture, low permittivity and loss, has high electric field magnitude throughout the cavity. Despite the high field magnitude the low loss of the material limits the power that can be absorbed and reduces the heating efficiency.

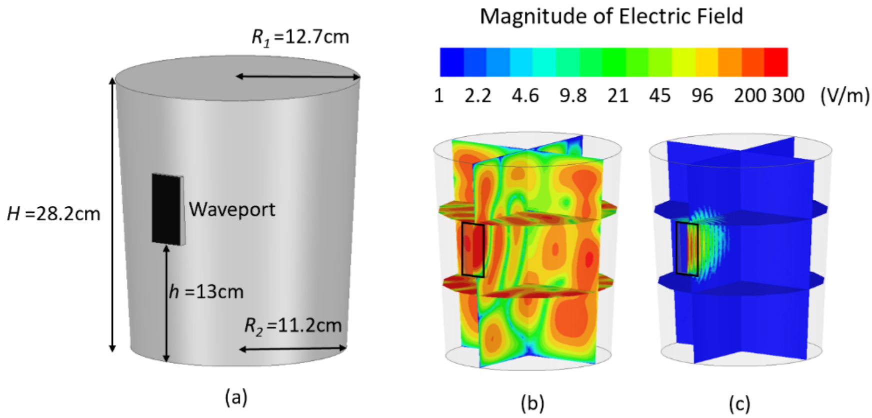

Fig 2. Simulated magnitude of the electric field for a single waveguide port excitation of a cavity completely filled with various materials. (a) Simulated cavity with dimensions labeled. (b) Cavity filed with food mixture $\varepsilon_r = 42$ and tanδ = .3, and (c) Cavity filled with LDPE and polystyrene $\varepsilon_r = 2.25$ and tanδ = .0003. The field value is normalized to a 1W incident power at 2.45 GHz on waveguide port.

Thermal Heating Rate Simulations

The electrical and chemical processes that occur when there is an electromagnetic field inside a material are linked through the heating rate caused by Joule losses as:

$$\sigma|E(x,y,z)|^2 = \rho c \frac{dT(x,y,z)}{dt} - \nabla \cdot (\kappa \nabla T(x,y,z)) \tag{3}$$

where ρ is the mass density of the filling material, c is the specific heat of the material, T is the temperature at a specific point within the material, and κ is the thermal conductivity. An analytical solution for the heating rate is complicated since the temperature and electric field are functions of position. Therefore, multi-physics simulations were used to determine the temperature increase due to Joule losses and account for the anticipated energy leakage through the cavity walls with thermal insulation as shown in Fig. 3.

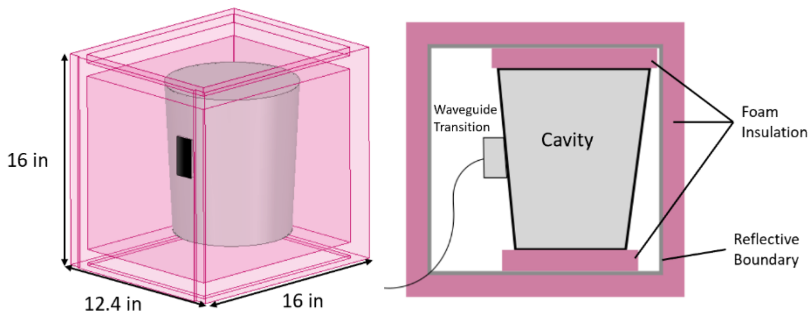

Fig. 3. Image of thermal simulation set up and a side cut of the insulation used in the simulation. The cavity filling is coupled to the field simulation as a thermal source. The cavity walls are 1mm thick tin-plated steel, the reflective surround has a reflectivity of 94% and the foam insulation is 1in thick XPS rigid polystyrene.

Using Ansys Workbench to connect the electromagnetic field data from Ansys HFSS and thermal excitation in Ansys Mechanical, heating rates are determined for several input power levels and two internal cavity operating temperatures, the results are shown in Table 1. These will be used to make an upper estimate of the RF power needed to obtain the specified heating rate required for pyrolysis processes.

Table 1. Simulated heating rates for given material input power and temperature

Material	Input RF Power (W)	Heating Rate at 25°C (°C/min)	Heating Rate at 400°C (°C/min)
LDPE and Polystyrene	500	.8	.01
	3000	5	1
Textiles	500	16	14
	3000	75	65
Food	500	100	90
	3000	650	600
Paper	500	44	40
	3000	320	310

Pyrolysis Process

The approximation for input materials, output materials, and process requirements for the system are obtained from four reference papers [7-10] which describe pyrolysis for various materials. The cited experiments, with input parameters detailed in Table 2, deal with slow pyrolysis systems that are sealed and operated without catalysts over one hour or longer time periods.

Table 2. Input parameters for several pyrolysis examples with single materials

Material	Input Caloric Value (MJ/kg)	Heating Rate (°C/min)	Duration of Heating (min)	Max Temperature (°C)	Time at Max Temp. (min)
LDPE and Polystyrene [7]	44	10	40	425	60
Textiles [8]	28	5	105	550	60
Food [9]	15.7	10	52	500	240
Paper [10]	13.6	10	85	873	60

The compounds, composition, and corresponding caloric values of the chemical outputs for the various pyrolysis processes were determined in the references using spectroscopic methods. A summary of the chemical outputs for each process are summarized in Table 3.

Table 3. Output Parameters for Pyrolysis

Material	Gas Caloric Value (MJ/kg)	Percent weight Gas (%)	Oil Caloric Value (MJ/kg)	Percent weight Oil (%)	Biochar Caloric Value (MJ/kg)	Percent weight Biochar (%)
LDPE and Polystyrene [7]	50.8	10	40.4	89.5	N/A	0.05
Textiles [8]	N/A	45.44	11.49	24.7	31.73	13.28
Food [9]	0.22	7.41	8.01	32.29	7.55	60.3
Paper [10]	N/A	15.0	21.8	19.0	11.7	43.0

Total Efficiency

Four different waste materials and mixtures are analyzed and the conversion efficiencies are calculated for filled cavities with dimensions as in Fig.2. The input and output parameters from Tables 2 and 3 are used for the material inside the cavity. The CW RF power required for each waste material to attain the heating rates from Table 2 are estimated by extrapolating the applied power and heating rate simulations from Table 1. Assuming a 70% DC to RF efficiency the DC power is calculated for each material. The DC energy is computed by multiplying the DC power by the operating times in Table 2. The conversion efficiency is defined as

$$\eta = \frac{W_{Ch,OUT}}{W_{Ch,IN}+W_{DC}} \tag{4}$$

where $W_{Ch,OUT}$ and $W_{Ch,IN}$ are the output and input chemical energies, and W_{DC} is the input dc electrical energy. Fig. 4 shows the simulated electric field magnitude for the 4 cases at 2.45GHz, and Table 4 summarizes the calculated efficiency using equations (2), (3) and (4).

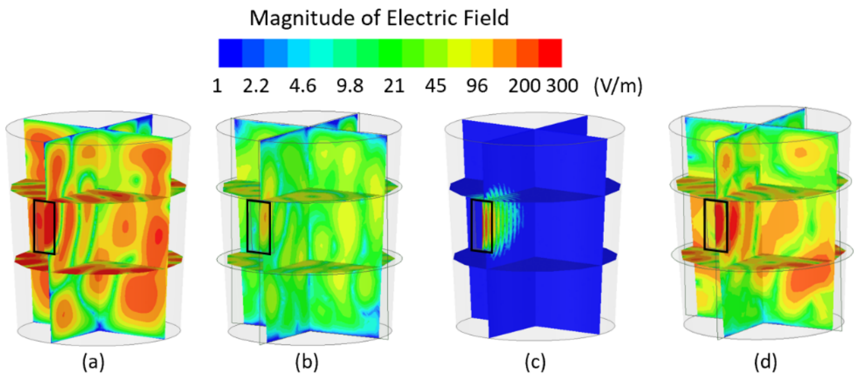

Fig.1. Simulated magnitude of the electric field, with 1W incident power at 2.45 GHz, inside cavities completely filled with (a) LDPE and Polystyrene, ε_r of 2.25, tanδ of .0003, thermal conductivity of .28 W/m°C, density of 950 kg/m^3 and specific heat of 2300 J/kg°C, (b)

Textiles, ε_r of 3, tanδ of .0003, thermal conductivity of .05 W/m°C, density of 1100 kg/m^3 and specific heat of .33 J/kg°C, (c) Food mixture, ε_r of 42, tanδ of .3, thermal conductivity of .85 W/m°C, density of 950 kg/m^3 and specific heat of 1.7 J/kg°C, and (d) Paper, ε_r of 2.2, tanδ of .03, thermal conductivity of .05 W/m°C, density of 1150 kg/m^3 and specific heat of .33 J/kg°C.

Table 4. Summary of Full System Efficiencies

Material	Input Caloric Value (MJ)	Output Caloric Value (MJ)	DC Energy (MJ)	Conversion Efficiency (%)	Output Energy compared to Input DC Energy (%)
LDPE and Polystyrene	545	548	96.8	85.4	566
Textiles	480	121	26.1	23.9	464
Food	202	92	12.2	43.0	754
Paper	136	92	16.0	60.5	575

Conclusion

In summary, simulations of microwave heating at 2.45GHz indicate that it can be effectively used for pyrolysis of various types of waste material. The simulations are performed with a cylindrical thermally-insulated over-moded metal cavity with a single waveguide feed. Future work includes adding more feeds and an investigation power and volume scaling using solid-state sources for smaller volumes and magnetrons for larger volumes where higher power is required.

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