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Continuous Heating Microwave System Based on Mie Resonances

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Abstract. Nowadays microwave heating is a part of many people's daily life, whereas industrial microwave heating is not as widespread. The permittivity of many liquids is highly temperature dependent, which makes it difficult to control the heating process when using microwaves. Presently, we propose two continuous heating microwave systems for heating, pasteurization and sterilization of liquids. Both designs utilize resonances in cylindrical water-filled cavities of different sizes so that high absorption through the whole heating process is achieved. The proposed systems can heat water from 0 to 100 °C, and their effectiveness is significantly higher than that of a single water cavity.

1. Introduction

Electromagnetic resonances in dielectric structures have been studied for many years, but their interest have increased intensively in the recent years with the high attention focused on all-dielectric metamaterials (MMs) [1]. The focus is predominantly in the mid-infrared up to the near ultraviolet due to the lack of magnetic response at those frequencies. In order to effectively excite resonances in dielectric structures, high-permittivity materials are required. The resonances enhance the scattering, however, if losses in the dielectric are significant, most of the extinct energy will be absorbed [2].

At microwave frequencies, several high-dielectric materials exist, and recently, it was shown that water can also be used for MM design due to its high permittivity [3]. With its abundance, bio-friendliness, low-cost and flexibility, water is attractive in materials for wave manipulation, sensing and absorption [3–5], to mention a few. The latter has been studied the most so far as water is quite lossy from 2–100 GHz at room temperature [5]. The absorbed energy in these structures is dissipated as heat, which increases the temperature of water just like in household microwave ovens operating around 2.45 GHz. In fact, the heating of food is often related to the water content [6]. Even though the microwave oven is a common household appliance, industrial microwave heating is not that widespread. Some of the advantages of microwave heating (volumetric heating) compared to conventional heating (surface heating) are the inverse heating profile, non-contact heating and fast on/off switching [7]. Both the permittivity of the dielectric and the geometry plays an important role for the absorption. Since the permittivity of liquids in general is temperature dependent, it is difficult to design a system with a uniform absorption profile for all temperatures. For liquids, the cylindrical geometry is the most preferred for continuous heating systems, and such systems already exist in the industry [8]. Presently, we propose two solutions operating at 2.45 GHz utilizing Mie resonances in



water cylindrical containers to heat water from 0 to 100 °C. We focus on making the absorption profile temperature-independent. We use the model for pure water from [9] and COMSOL Multiphysics 5.3 to simulate the heating systems [10]. In our modelling, we do not include convection and heat radiation. Throughout the work, the time-factor $\exp(j\omega t)$, with ω being the angular frequency and t being the time, is assumed and suppressed.

2. Heating of water in cylinders

The absorbed electromagnetic power in water can be found through Maxwell's equations with the final result given by [11]

$$P_{\text{abs}} = \frac{1}{2} \omega \varepsilon_0 \varepsilon''_{r,w} \int_{V_w} |\mathbf{E}_w|^2 dV, \quad (1)$$

where $\varepsilon_w = \varepsilon_0 \varepsilon_{w,r} = \varepsilon_0 (\varepsilon'_w - j\varepsilon''_w)$ is the permittivity of water, V_w is the volume of water, \mathbf{E}_w is the electric field in water and dV is the differential volume element. To maximize the absorbed power both ε''_w and \mathbf{E}_w should be high. However, as ε''_w increases, \mathbf{E}_w usually decreases. The relative permittivity of water is shown as a function of temperature at the frequency 2.45 GHz in figure 1(a). Both the real and imaginary permittivity decrease with increasing temperature.

In [12] we analyzed the scattering and absorption of both TM and TE plane waves incident on a water cylinder. Presently, we focus on the TE incidence exciting a magnetic dipole resonance in the cylinder. Due to the temperature dependency of water, different sizes of cylinders are needed at different temperatures to excite the required resonance. The absorption efficiency (Q_{abs}) is shown in figure 1(b) as a function of temperature at 2.45 GHz for four cylinders of different radii resonating for 12.5, 37.5, 62.5 and 87.5 °C. Interestingly, the cylinders designed for higher temperatures have a higher absorption even though the losses are lower at these temperatures. However, it is in fact the higher losses at lower temperatures that cause the lower absorption by deteriorating the intensity of the resonance and hence the electric field in equation (1). As Fig.1(b) shows, none of the cylinders have a wide enough absorption band to cover all temperatures, whereas together they potentially have.

3. Water heating systems

In general, rectangular waveguides are used to transfer high-power microwaves. Presently, we use a WR-430 waveguide with the cross section 109.2 mm × 54.6 mm, see Figure 2(a). With the cylinders investigated in section 2, we come up with two systems to heat water. One (Design A) is a single channel waveguide with four connected cylinders going through it as shown in figure 2(b). The cylinders are the ones studied in section 2. Water flows into the first cylinder at a temperature of 0 °C and is heated to 25 °C when it leaves it. Subsequently, it flows into the second cylinder, where it is

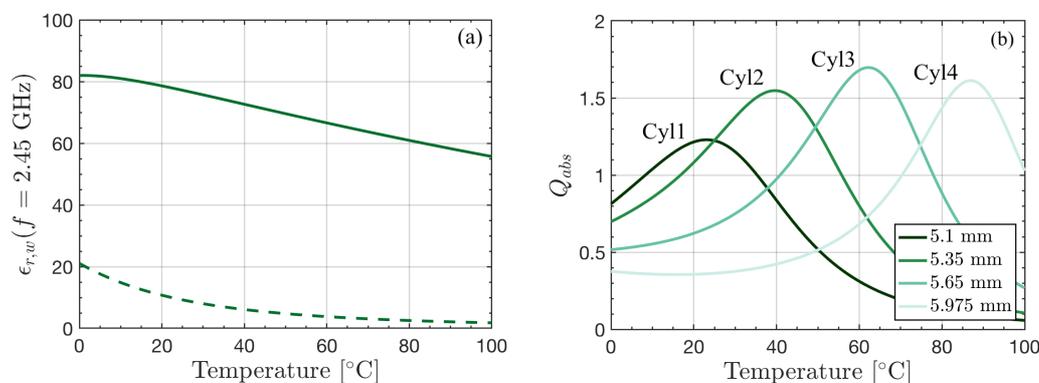


Figure 1. Relative permittivity of water in (a) and absorption efficiency of TE plane wave incidence on cylinders of different radii as a function of temperature in (b).

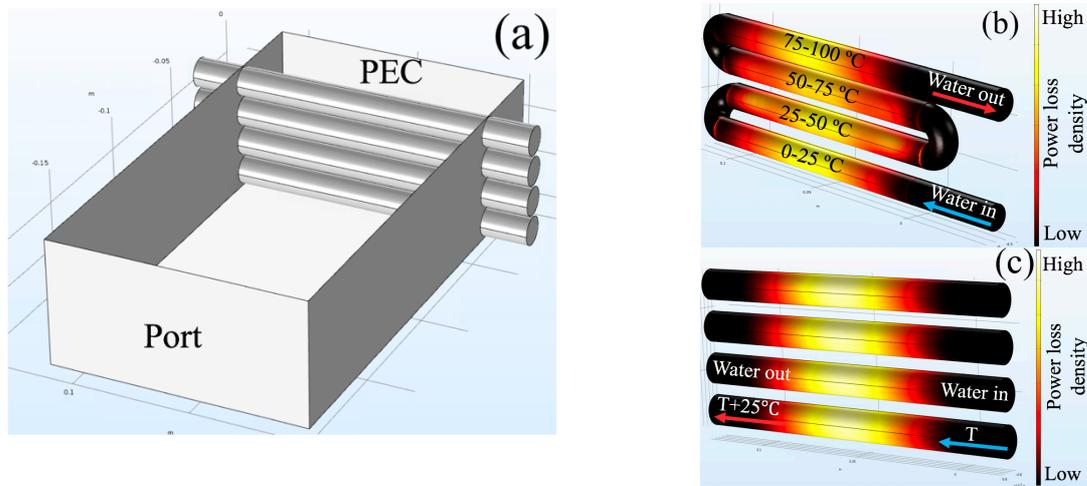


Figure 2. Sketch of water heating system in (a), Design A in (b) and Design B in (c) with the power absorption profile.

heated to 50 °C. This process continues until water leaves the fourth cylinder, where it reaches a temperature of 100 °C. The other design (Design B) is a four-channel waveguide with four cylinders going through them as shown in figure 2(c). As the four cylinders go through each waveguide channels, their radius is varied. In each waveguide channel, water is heated by 25 °C, so that 0 °C water is heated to 100 °C at the output.

The systems were implemented into COMSOL Multiphysics 5.3 in a waveguide model, which is shown in figure 2(a). We cancel the transmission by putting a PEC surface behind the cylinders, so we only have to minimize reflection. The input power (P_{in}) is set to 1 W, and hereafter the systems were optimized by slightly adjusting the positions of the cylinders and/or their sizes. The final results for absorbed power as a function of temperature for both designs are shown in figure 3. The power loss density is included in figure 2(b) and (c) illustrating where the heating happens in the cylinders. We can calculate the absorption in each cylinder to see if some cylinders absorb more than others. We want to have as uniform absorption profile as possible, since the least absorbing cylinder will be the bottleneck of the system. In figure 3(a), the temperature in each cylinder is changed by ΔT , and the temperature range for each cylinder is given in the legend. In average, the absorption is around 21-23 % in each cylinder or 89 % in total. However, their volumes are slightly different, and the smallest cylinder will need least energy to heat it. This can be seen from the time it takes to heat water

$$t_{\Delta T}^n = c_w \rho_w \Delta T V_w^n / P_{abs}^n, \quad (2)$$

where c_w is the heating capacity of water and ρ_w is the density of water and n designate the cylinders. The average absorption for each waveguide channel in Design B is 85 – 96 % with a total of 92 %. For reference, the results for a slab of water with similar volume as four cylinders is included in figure 3(b).

By using equation (2), we can calculate the amount of water (in mL) that can be heated from 0 to 100 °C per 1 kJ microwave energy that is put into the system. If everything is absorbed, this is 2.40 mL/kJ. For Design A, this is determined by the slowest heating cylinder and amounts to 2.06 mL/kJ, which is 86 % of the maximum possible (2.40 mL/kJ). For Design B, we can control the power going into each waveguide channel to compensate for the lower/higher absorbing cylinders. If doing so, we achieve an output of 2.22 mL/kJ (93 %). For comparison, this is only 0.99 mL/kJ (42 %) for the associated water slab.

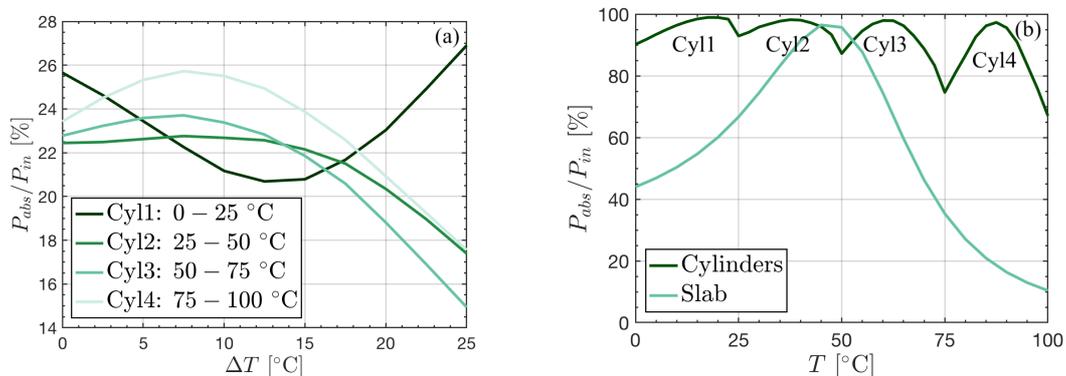


Figure 3. Absorption as a function temperature for Design A in (a) and Design B in (b). Summing the graphs in (a) gives the total efficiency of Design A.

4. Conclusions

We proposed two continuous heating systems, where Mie resonances in cylinders are used to heat water. Both designs had high absorption from 0 to 100 °C, which could not be achieved for a single structure. One design was compact (single waveguide), but had a slightly lower output and was more difficult to control compared to the other design consisting of four cascaded waveguide channels. The proposed heating systems may have possible applications within reheating, pasteurization and sterilization processes.

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