THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF RESONANCE FREQUENCIES IN A MICROWAVE HEATED FLUIDIZED BED REACTOR

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Abstract

Fluidized bed reactors have large potential for use in high purity silicon chemical vapor deposition with microwaves as the energy source. Lowest resonance frequency modes of a cylindrical fluidized bed reactor (cavity) are theoretically and experimentally investigated. The behavior of resonant frequencies is examined with respect to varying dielectric properties. Experimental results are found to be in close agreement with theoretical predictions. The knowledge of resonant frequency behavior will help in designing and operating fluidized bed reactors efficiently.

Introduction

The utilization of microwaves as a source of energy for chemical processing has increased significantly in recent years. This is in part due to rapid volumetric heating ability of microwaves and other advantages such as decrease in energy costs and processing time. The dielectric properties of a material being processed by microwaves may change considerably during heating because of increased temperature and/or varying process conditions. Then, understanding the dynamic behavior of the heating process over a wide range of operating conditions becomes a difficult task. The production of high purity silicon using microwaves in a fluidized bed reactor has been under study in this laboratory. The dielectric properties of silicon were found to change considerably during the heating process as a function of temperature and particle size. As a part of the ongoing project, the dielectric properties of high purity silicon were measured as a function of temperature and particle size [1]. The dielectric property variation during the heating process was confirmed. Under the varying dielectric properties, the resonant modes existing in the reactor will also change. Then, information on mode tuning behavior becomes important. The uniformity of temperature distribution becomes a concern when propagating modes vary. The tuning behavior of the reactor may theoretically be determined with known dielectric properties and material thickness in the reactor. Theoretical calculations are normally in good agreement with experimental results for lossless materials. For lossy materials, differences between theoretical and experimental results tend to be larger.

Although some theoretical work has been reported in the literature on the behavior of mode tuning of loaded rectangular cavities, very little work has been done to investigate the behavior of mode tuning of loaded cylindrical cavities. Mihran [2] reported the mode tuning of a rectangular cavity with a lossy dielectric slab at the bottom of the cavity. El-Deek and Farghaly [3] investigated theoretically the effect of varying the location of the dielectric load on the resonance frequency in rectangular microwaves ovens. Mladenovic et al [4], studied the tuning of a rectangular cavity loaded with multilayer lossy dielectric slabs. The above studies were based on the transverse resonance method with the impedance resonance condition.

In this paper the mode tuning behavior of an actual experimental fluidized bed reactor is investigated theoretically and experimentally for both lossless and lossy dielectrics. Theoretical results are obtained for the lowest TE and TM mode resonance frequencies as a function of the dielectric sample height in the cavity. Experimental results are also reported as a function of height of the lossless and lossy dielectric material.

Theoretical Approach

Consider the cylindrical cavity given in Fig. 1a. The four layers identified in the cavity represent the different regions present in the experimental reactor. Layer 1 is an air-filled region above the dielectric, layer 2 is the dielectric, layer 3 is a perforated quartz distributor plate and layer 4 is an air-filled space between the distributor plate and the aperture. Regions 1, 3 and 4 are considered lossless in the theoretical analysis. The dielectric material in region 2 is considered to have a complex dielectric constant. Referring to the equivalent transmission line shown in Fig. 1b, a reference plane may be located at the top surface of medium 2 (air-dielectric interface). At resonance, the impedance looking in the +z direction must equal the negative of the real value of the impedance seen in the -z direction. The following expression for the equivalent circuit may then be derived,

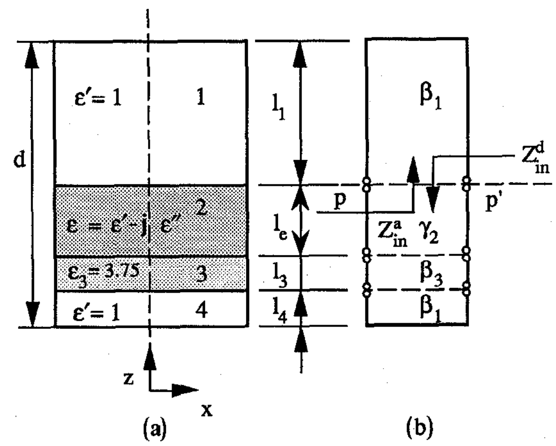

Fig. 1. (a) A cylindrical cavity loaded with a lossy dielectric located at a height (l_3+l_4). (b) equivalent circuit.

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$$\frac{\text{Tan}(\beta_1 l_1)}{\beta_1} + \frac{\text{Tan}(\beta_1 l_4)}{\beta_1} + \frac{\text{Tan}(\beta_3 l_3)}{\beta_3}$$

$$- \frac{\beta_3}{\beta_1^2} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_1 l_4) \text{Tan}(\beta_3 l_3) =$$

$$- \text{Re} \left(\frac{\text{Tanh}(\gamma_2 l_e)}{\gamma_2} + \frac{\gamma_2}{\beta_1^2} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_1 l_4) \text{Tanh}(\gamma_2 l_e) \right.$$

$$+ \frac{\gamma_2}{\beta_1 \beta_3} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_3 l_3) \text{Tanh}(\gamma_2 l_e)$$

$$\left. - \frac{\beta_3}{\beta_1 \gamma_2} \text{Tan}(\beta_1 l_4) \text{Tan}(\beta_3 l_3) \text{Tanh}(\gamma_2 l_e) \right) \quad (1)$$

where β_1 and β_3 are phase constants in region 1,4 and 3, respectively. The complex propagation constant γ_2 in the dielectric is given by,

$$\gamma_2 = \alpha_2 + j \beta_2 \quad (2)$$

where α_2 is the attenuation constant and β_2 is the phase constant in medium 2. For TE modes,

$$\alpha_2 = \left(\frac{1}{2} \left(\frac{\omega_r^2 \varepsilon'}{c^2} - \left(\frac{X'_{np}}{R} \right)^2 \right) \left(\left(1 + \left(\frac{\frac{\omega_r^2 \varepsilon''}{c^2}}{\frac{\omega_r^2 \varepsilon'}{c^2} - \left(\frac{X'_{np}}{R} \right)^2} \right)^2 \right)^{1/2} - 1 \right) \right)^{1/2} \quad (3)$$

$$\beta_2 = \left(\frac{1}{2} \left(\frac{\omega_r^2 \varepsilon'}{c^2} - \left(\frac{X'_{np}}{R} \right)^2 \right) \left(\left(1 + \left(\frac{\frac{\omega_r^2 \varepsilon''}{c^2}}{\frac{\omega_r^2 \varepsilon'}{c^2} - \left(\frac{X'_{np}}{R} \right)^2} \right)^2 \right)^{1/2} + 1 \right) \right)^{1/2} \quad (4)$$

where R is the diameter of the reactor and X'_{np} represent the zeros of the derivative of the Bessel's function. For TM modes, X'_{np} is replaced by X_{np} which is the zeros of the Bessel's function. In equation (3) and (4), ω_r is the angular resonance frequency and c is the speed of light. If the dielectric in medium 2 is relatively lossless, equation (1) may be simplified to obtain the following equation,

$$\frac{\text{Tan}(\beta_1 l_1)}{\beta_1} + \frac{\text{Tan}(\beta_1 l_4)}{\beta_1} + \frac{\text{Tan}(\beta_3 l_3)}{\beta_3}$$

$$- \frac{\beta_3}{\beta_1^2} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_1 l_4) \text{Tan}(\beta_3 l_3)$$

$$= - \left(\frac{\text{Tan}(\beta_2 l_e)}{\beta_2} - \frac{\beta_2}{\beta_1^2} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_1 l_4) \text{Tan}(\beta_2 l_e) \right.$$

$$- \frac{\beta_2}{\beta_1 \beta_3} \text{Tan}(\beta_1 l_1) \text{Tan}(\beta_3 l_3) \text{Tan}(\beta_2 l_e)$$

$$\left. - \frac{\beta_3}{\beta_1 \beta_2} \text{Tan}(\beta_1 l_4) \text{Tan}(\beta_3 l_3) \text{Tan}(\beta_2 l_e) \right) \quad (5)$$

The phase constants β_1 and β_3 are given by,

$$\beta_1 = \left(\frac{\omega_r^2}{c^2} - \left(\frac{X'_{np}}{R} \right)^2 \right)^{1/2} \quad (6)$$

and

$$\beta_3 = \left(\frac{\omega_r^2 \varepsilon_3}{c^2} - \left(\frac{X'_{np}}{R} \right)^2 \right)^{1/2} \quad (7)$$

Equations (1) and (5) are the transcendental equations describing the tuning behavior of propagating TE and TM modes in a cylindrical cavity loaded with lossy and lossless dielectric located at a height of $(l_3 + l_4)$ above the bottom.

Calculations were performed for a cylindrical cavity of internal dimensions of 8.06 inches diameter and 27.5 inches height. The distance between the quartz distributor plate and the aperture (l_4) was 0.2 inches while the quartz plate (l_3) was 0.1875 inches thick. The above dimensions are for the experimental fluidized bed reactor shown in Fig. 2. The actual reactor has a dome shaped upper head which was approximated to have a 2 inch equivalent reactor height. The height of the cylindrical section of the reactor was 25.5 inches including regions 3 and 4. Thus, the total height of the reactor was approximated to be equivalent of 27.5 inches of cylindrical height. Resonance frequencies for the lowest TE and TM modes were computed for two cases. In the first case, the dielectric in medium 2 was assumed lossless with a dielectric constant (ε') of 3.5. In the second case, It was assumed complex with ε' of 8.1 and loss factor (ε'') of 0.95.

Experimental approach and results

The experimental system shown in Fig. 2 was used for resonance frequency measurements. The low power network analyzer system is coupled to the reactor via a coaxial cable. A loop located at the center of the upper head of the reactor is used to introduce the microwaves to the reactor. At the bottom of the reactor is the aperture above which the quartz distributor plate is located. During microwave heating experiments, microwaves were introduced to the reactor through the aperture via a waveguide system extending from a 30 KW microwave generator. The bottom of the reactor was sealed at the lower side of the aperture to form a cavity for the experiments reported here. This configuration was kept to simulate the conditions existing during the microwave heating experiments. This set up is the same as the configuration under the heating experiments with the exception that signal is introduced to the reactor through the loop instead of the aperture as shown in Fig. 2.

Although this study is not concerned with the excitation of modes, the lower TE modes and TM modes were excited with a

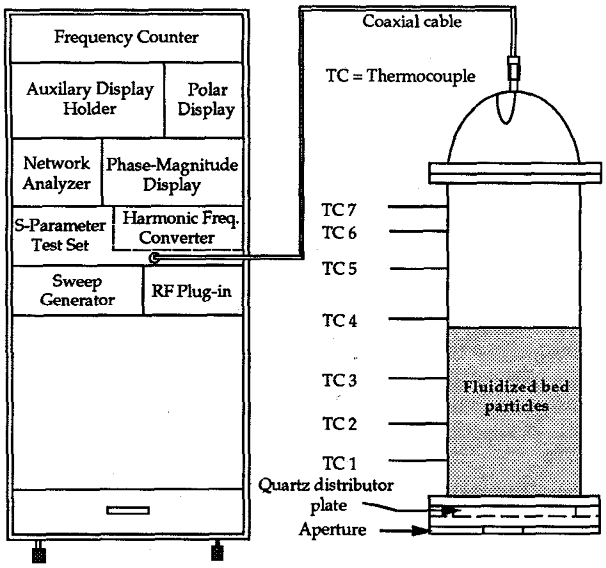

Fig. 2. Experimental set up for resonance frequency measurements.

loop inserted through the upper head of the reactor. The resonance frequencies of the reactor shown in Fig.2 were measured as function dielectric thickness (l_e) for two samples. Pyrolysis alumina (Al_2O_3, 75-420 µm particle size) was used as a lossless sample. The dielectric properties of this material have been measured previously [5]. Pyrolysis alumina has a dielectric constant (ε') of 3.5 and loss factor (ε'')of 0.015 at room temperature. Since the loss factor is low, the theoretical results were computed assuming a lossless material. In fact, repeating the calculations with a loss factor of 0.015 produced practicallythe same results as the lossless case.

The second dielectric used for resonance frequency experiments was a silicon sample of 500-800 µm particle size which was contaminated and had a relatively high loss factor. Utilizing the resonance cavity method [1] the dielectric constant and loss factor of the silicon sample at room temperature were determined to be 8.1 and 0.95, respectively. Hence, this material was a good choice for investigating its mode tuning effects.

It must be noted that both the alumina and silicon samples were in particulate form. Previous mode tuning studies have used either slabs or water samples whish did not impose the problem of leveling the surface of the material and difficulty of measuring the sample height in the cavity.

Theoretical and experimental results for TE_{111} through TE_{116} modes for alumina are plotted in Fig. 3. The resonance frequency data were taken at 0.25 inch increments between 0 to 2 inches and at 0.5 inch increments between 2-8 inches. The experimental results show a good agreement with theoretical results. The resonance frequency curves fall in a stairstep fashion. A frequency difference of approximately 15 MHz exists between theoretical and experimental results for all modes shown in Fig. 3. This difference is probably due to the height approximation made for the reactor upper head in the theoretical calculations. The fact that the amplitude of the error stays constant for the empty and loaded cavity suggest that this error is due to the height approximation of the reactor in the theoretical calculations.

In Fig. 4, theoretical and experimental results for TM_{013}, TM_{014} and TM_{015} modes for alumina are plotted. The experimental results for the TM modes display a slightly different behavior compared to the TE modes. The measured TM resonance frequencies decrease smoothly with increased dielectric sample height. The decrease is almost linear. Only the TM_{015} mode exhibits a slightly falling stairstep behavior. The general trend of the resonance frequencies, however, is consistent with the increased sample height. This type of behavior was also observed for the lossy sample experiment.

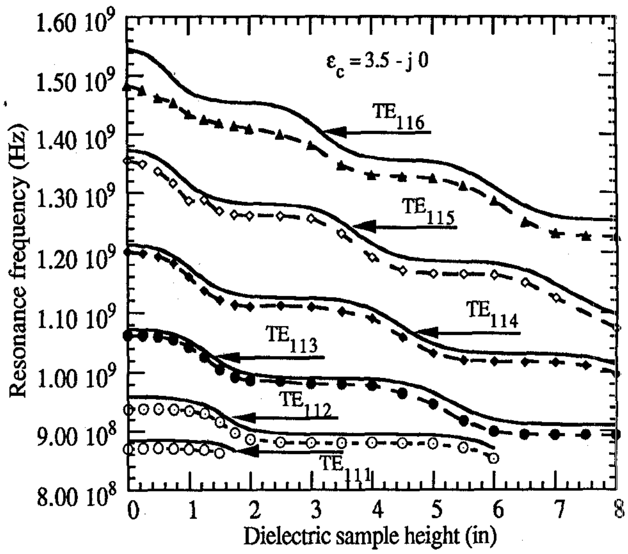

Fig. 3. Measured and computed Resonance frequencies of TE_{111} through TE_{116} mode versus alumina height in the reactor. Solid lines: calculated, Dashed lines: measured.

The results for the lossy silicon sample are plotted in Fig. 5. In general, experimental results are in close agreement for lower TE modes. The resonance frequencies for higher order modes could not be positively identified and differentiated from each other and therefore are not reported here. In the theoretical analysis for the lossy material, the number of modes in the z direction is taken as the number of half wavelengths (or number of standing wave maxima) in the air-filled region above the dielectric. With this mode numbering system, the resonant frequency follow an upward-rising stairstep. This notation is helpful for lossy dielectrics. It is observed that the steepness of the frequency rise decreases as the loss factor increases. For even higher losses, the resonance frequency approaches to the frequency of the empty cavity with the dielectric surface replaced by a conductive plate. In Fig. 5, the slowly upward-rising curves represent the theoretical resonant frequencies of the reactor above the dielectric surface where the dielectric is replaced by a conductive plate. As suggested by theory, the resonant frequencies will approach the slowly upward rising curves if the measurements are taken for a highly lossy material. Unlike the results for lossless material, the results for lossy material show fluctuation as the dielectric height is increased.

The results obtained here give an insight as to the propagation modes at different dielectric material heights for the two samples considered. The dielectric material height in the reactor may be varied to obtain a certain resonating mode at a given frequency. Furthermore, the resonance frequency information is useful in designing proper cavities for heating applications for different dielectric materials.

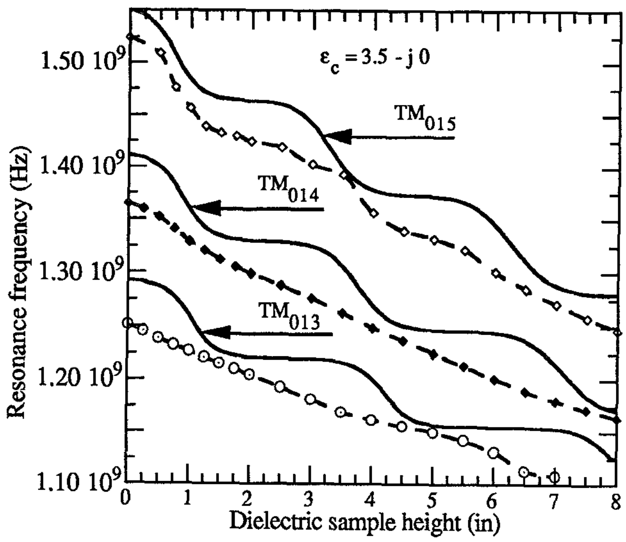

Fig. 4. Computed and measured TM_{013}, TM_{014} and TM_{015} mode resonance frequencies of the reactor versus alumina height. Solid lines: calculated, Dashed lines: measured.

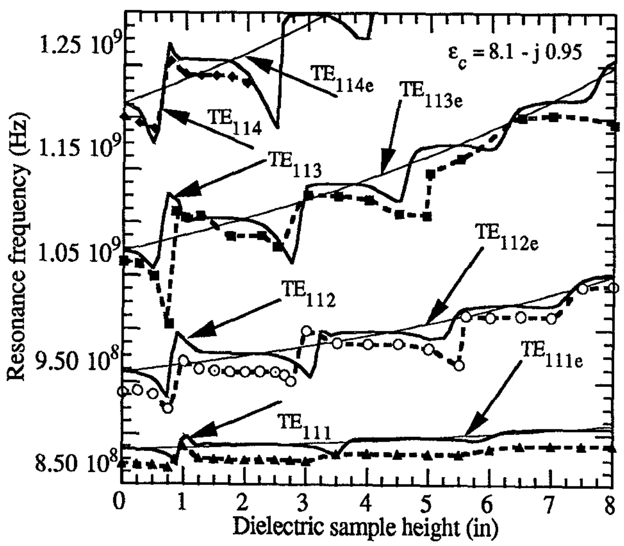

Fig. 5. Computed and measured first four TE mode resonance frequencies of the reactor versus silicon height. Solid lines: calculated, Dashed lines: measured.

Conclusion

The mode tuning characteristics of a fluidized bed reactor have been investigated. The lower order TE and TM mode resonance frequencies have been computed and measured as a function of dielectric height for two different samples. The effect of loss was included in the theoretical analysis. The theoretical results were obtained using the transverse resonance method. Good agreement between measured and computed resonance frequencies was obtained. The TE mode resonance frequencies for the lossless alumina sample show a stairstep fall as a function of the dielectric sample height. The TM modes follow a more smoothly decreasing behavior. The results for the lossy silicon sample exhibited an upward raising stairstep behavior.

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