Heating dielectric samples in a waveguide

Stanley Humphries, Ph.D.

Field Precision LLC
E mail: techinfo@fieldp.com
Internet: https://www.fieldp.com

Recently I had an inquiry from a user interested in microwave heating of dielectric samples in a air-filled waveguide. The application presented a good opportunity to apply the recently-developed capability for coupling **Aether** solutions to **HeatWave**, so I wrote and tested a set of template input files.

In the solution, the sample was suspended at the center of a rectangular waveguide that carried a traveling wave in the TE_{10} mode. The wave was polarized with E_y and the guide had dimensions $a = 10.0$ cm along x and $b = 8.0$ cm along y. The sample was a cylinder of radius 2.0 cm and height 3.0 oriented as shown in Fig. 1. Heating occurred via capacitive currents driven in the resistive object. The mesh had cubic elements with sides 0.1 cm for good resolution of the sample volume.

The first task was to generate a good approximation to a TE_{10} mode solution. For guidance, I followed Chap. 9 of the **Aether Tutorial Manual**, *TE10 mode in a rectangular waveguide*. The cutoff frequency was

$$f_0 = \frac{c}{2a} = 1.5 \text{ GHz}. \tag{1}$$

At a working frequency of $f = 2.0$ GHz, the vacuum wavelength was $\lambda_0 = 15.0$ cm and the ratio of the group velocity to the speed of light was:

$$\frac{v_g}{c} = \sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2} = 0.6614. \tag{2}$$

I modeled a waveguide section of length 20.2 cm. The mesh was built by defining a metal box with dimensions $W_x = 10.2$ cm, $W_y = 8.2$ cm and $W_z = 20.2$ cm. The interior was created by over-writing with an air box of dimensions $W_x = 10.0$ cm, $W_y = 8.0$ cm and $W_z = 20.2$ cm. Ideal absorbing layers of thickness $W_z = 0.1$ cm filled the entrance and exit. The entrance layer carried a current density

$$J_y = (1.0 \times 10^4)\ \cos(0.3142x). \tag{3}$$

When waves are normally incident, the conductivity for a matched absorbing layer is given by[1]:

$$\sigma = \frac{1}{\eta\, W_z} \ \ \text{(S/m)}, \tag{4}$$

where η is the characteristic impedance of the adjacent medium (377.3Ω for air). As discussed in the **Aether** tutorial, the value must be adjusted by v_g/c for modes in a waveguide. The calculated value is $\sigma = (0.6614)(2.654) = 1.756$ S/m. Figure 2 shows a plot of $|\mathbf{E}|$ in the plane $y = 0.0$ cm with the

[1] S. Humphries, **Finite-element Methods for Electromagnetics** (CRC Press, Boca Raton, 1997) Sect. 13.1

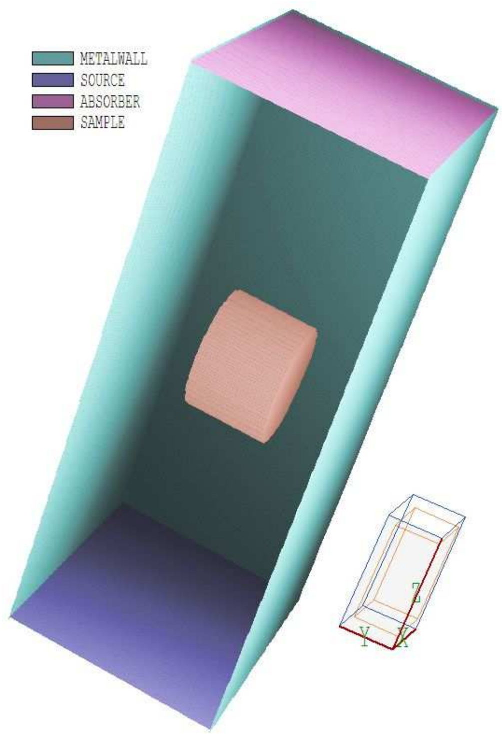

Figure 1: Mesh for the calculation showing the waveguide walls, the source and absorbing layers and the heated sample.

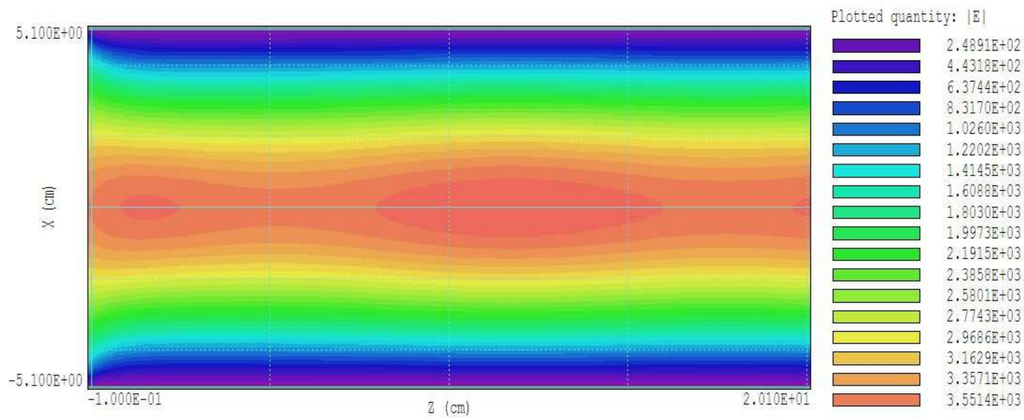

Figure 2: Plot of $|\mathbf{E}|$ for the TE_{10} mode with no sample.

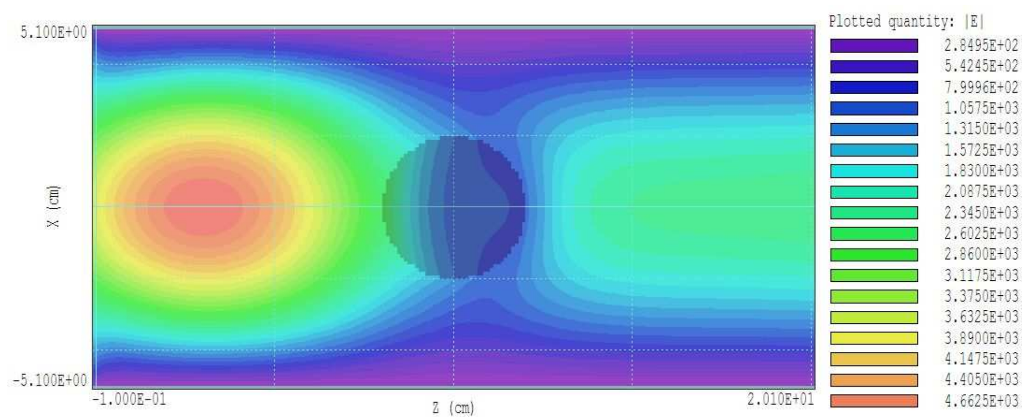

Figure 3: Plot of $|\mathbf{E}|$ for the TE_{10} mode with the sample present.

properties of the sample set to those of air. For an ideal traveling wave, the magnitude of the electric field should be constant in z.

If the heating is to be effective and the finite-element calculation accurate, the electric field should penetrate the object rather than concentrate in a thin surface layer (*i.e.*, field exclusion). I picked the following material properties: $\epsilon_r = 1.8$, $\mu_r = 1.0$ and $\sigma = 0.5$ S/m. Figure 3 shows the altered electric field when the sample is present. A substantial fraction of the electromagnetic power is reflected, resulting in an upstream standing-wave component. About half the power is transmitted as a downstream traveling wave and half is absorbed by the sample (19.2 W). Figure 4 shows the spatial variation of time-averaged power density in the sample in the plane $x = 0.0$ cm. The peak value is $p = 1.644 \times 10^6$ W/m^3.

The next step was to set up a **HeatWave** solution using the output from **Aether** as a thermal source. The goal of the calculation was to investigate

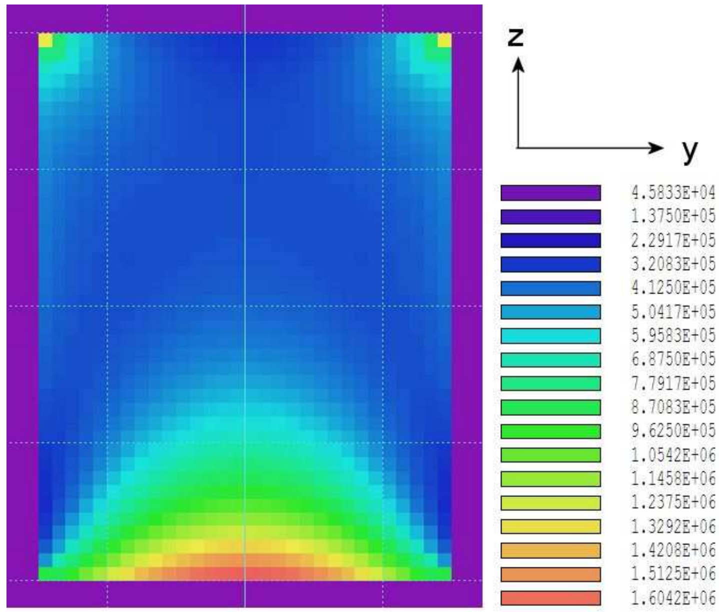

Figure 4: Power-density p in the sample, plot in the plane $x = 0.0$ cm.

heating of the sample and the surrounding air. Thermal effects in the virtual source and absorber layers are not of interest. Therefore, these regions along with the metal wall were set to the fixed-temperature condition $T = 0.0^o$C. The sample had thermal properties $k = 0.02$ W/m^2-^{o}C, $C_p = 2000.0$ J/kg-^{o}C and $\rho = 1000.0$ kg/m^3. The air region has properties k = 0.024 W/m^2-^{o}C, Cp = 1005.0 J/kg-^{o}C and $\rho = 1.293$ kg/m^3. Both the sample and air were at initial temperature $T = 0.0^o$C. The dynamic thermal calculation ran for $\Delta t = 10.0$ s. In the absence of thermal condition, the peak temperature in the sample is predicted to be

$$T_{max} = \frac{p\ \Delta t}{\rho\ C_p} = 8.22\ \ {}^o\text{C}. \tag{5}$$

Figure 5 shows the end result, the temperature in the sample and surrounding air at $t = 10.0$ s in the plane $x = 0.0$ cm. The temperature variation tracked the power-density profile of Fig. 4 with a peak value of 8.11^{o}C.

The complete set of input files is available to **Aether/HeatWave** users. To make a request, please contact us at `techinfo@fieldp.com`.

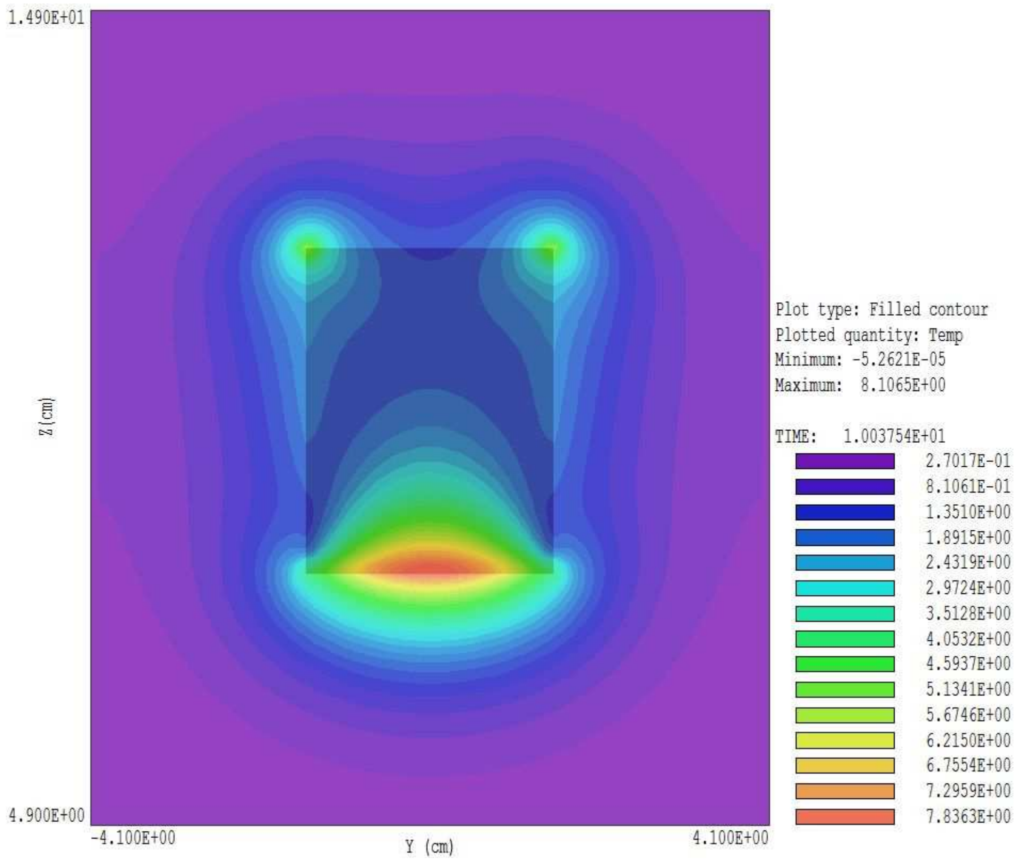

Figure 5: Temperature in the sample and surrounding air at 10 s, plot in the plane $x = 0.0$ cm.