

Microwave Launcher Design for Doppler Sensing in Chemical Looping Combustion

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Abstract: We report here on the use of the COMSOL emw (electromagnetic waves) module in the design of a microwave launcher. This launcher is to be used in a microwave Doppler sensor that is incorporated into a chemical looping combustion system. The launcher is designed in two steps. First, we determine the best mode for launching a wave into air from an overmoded cylindrical waveguide. We then develop a transition from a coaxial transmission line to the cylindrical waveguide.

Keywords: microwave, transition, launcher, boundary mode analysis

1. Introduction

In a chemical looping combustion system [1], oxygen carrier particles are saturated with oxygen in one reactor. These particles are transported to a combustion reactor where they react with gaseous or particulate fuel. When appropriately designed no nitrogen is transported into the combustion region, and consequently the exhaust is nearly pure carbon dioxide suitable for sequestration. Measurement of the mass flow rate of the oxygen carrier particles is required for process control in these combustion systems.

We are developing a microwave Doppler system suitable for mass flow rate measurements in a chemical looping combustion system. In a Doppler mass flow measurement microwave energy is directed at the moving stream of particles. The reflected wave is frequency-shifted by $\Delta f = 2f(v/c) \cos(\theta)$ where f is the microwave frequency, v is the velocity of the particles, c is the velocity of light, and θ is the angle between the microwave beam and the direction of flow. The intensity of the reflected microwave energy is proportional to the number of particles;

consequently the mass flow rate can be determined. Design of the microwave launcher is a challenge because the flow region is at high temperature (~900 C) and pressurized with respect to the environment.

In this paper we describe the application of COMSOL finite element simulations to the design of the microwave launcher. We first discuss launching a wave from a cylindrical waveguide into air, followed by the design of a transition from a coaxial transmission line to the cylindrical waveguide.

2. Equations

In the following sections we use the emw (electromagnetic waves) mode of COMSOL 4.2a or 4.3a. Calculations are performed in sinusoidal steady state using Frequency Domain analysis. In this mode COMSOL solves Maxwell's equations in the simulation domain. With two exceptions boundaries of the simulation domain were ideal conductors. An input port (either coaxial or numerical, as noted below) was used for excitation of the input wave. A perfectly matched layer (PML) was used to absorb all energy incident on the output port.

3. Launching a wave into air

An early design decision was made to inject the microwave energy into the flow region using a 2.54 cm diameter dielectric waveguide angled about 77 degrees with respect to the flow direction. This angle was chosen because according to Snell's law a plane wave will be bent to an angle closer to 45 degrees at the air-waveguide interface. The dielectric waveguide is made from alumina, which can tolerate the high temperatures in the chemical looping reactor and

provides a pressure seal between the flow region and the environment. Since the relative permittivity of alumina is about 9, the wavelength at 10 GHz is only 1 cm and a large number of travelling modes can exist in the 2.54 cm waveguide (Table I). Such a waveguide is referred to as an *overmoded* waveguide.

We first investigated launching a wave from the alumina dielectric waveguide into air. Since many modes can exist we performed simulations using the emw mode of COMSOL 4.2a in order to determine which mode is desired. Figure 1 shows the geometry simulated. The alumina waveguide emits microwave energy into a half-sphere. The half-sphere is enclosed by a region implementing the perfectly matched layer boundary condition. At the entrance of the alumina waveguide the numerical port boundary condition is imposed. To determine the mode shape at this input port, boundary mode analysis is performed (see Appendix for details). This is followed by frequency domain analysis and determination of the S_{11} parameter from the final solution.

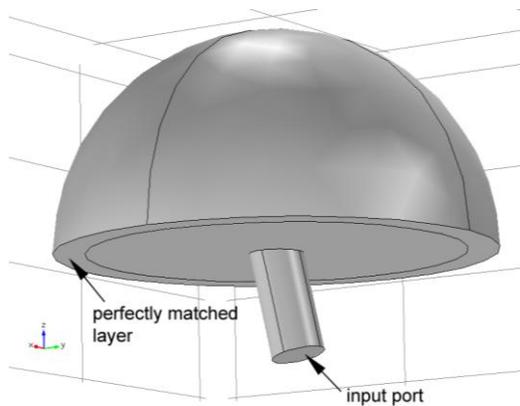


Figure 1. Geometry for simulation.

Table I shows the computed S_{11} at the operating frequency of 10 GHz for several modes. The modes are designated by the wavenumber in the direction of propagation. We see that almost all of the incident energy is reflected except for the modes at $k = 579$ and 611 cm^{-1} . One component of the electric field in the plane of the port for the 611 cm^{-1} mode is plotted in Figure 2. Referring to the analytic mode shapes [2] this can be identified as the TE_{11} mode. Note that this mode is very similar to a plane wave.

mode (out-of-plane wavenumber, m^{-1})	S_{11} (dB)
281	-2.30
327	-0.38
366	-0.40
461	-0.36
463	-0.41
475	-2.53
531	-1.18
548	-2.38
579	-7.61
598	-2.02
611	-5.59

Table 1. Simulated S_{11} for several modes when a wave is launched from the cylindrical waveguide into free space.

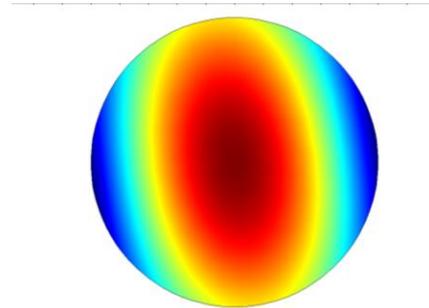


Figure 2. Electric field in the y direction at the input port for the 611 m^{-1} mode.

It is desirable that the microwave energy be mostly emitted at an angle with respect to the flow direction. Figure 3 shows the total power density as a function of angle. We can see that the beam is deflected as expected according to Snell's law.

It is worth noting that there are actually two degenerate modes for a circular port. It can be determined that the preferred mode has the electric field vector oriented parallel to the axis of rotation of the cylinder. Figure 3 shows the energy density for that preferred direction.

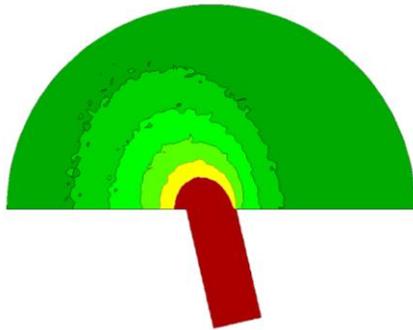


Figure 3. Total energy density as a function of position in the plane perpendicular to the axis of rotation of the cylinder.

4. Coaxial-to-circular waveguide transition

This section describes analysis of three coaxial-to-circular waveguide launcher designs. We seek a design with a good match to a 50 ohm coaxial transmission line (low S_{11}) which excites the desired TE_{11} mode in the circular waveguide. The simulations were performed by imposing the port boundary condition with an incident power of 1 W at the input of a coaxial transmission line with a characteristic impedance of 50 Ω . The circular waveguide region was 5 cm long and was terminated by a Cartesian perfectly matched layer (PML). Frequency domain analysis was performed at 10 GHz and the parameter S_{11} was determined from the solution.

4.1 Axial launcher

In the axial launcher the coaxial line is located at the axis of the 2.54 cm diameter alumina circular waveguide. The center conductor is extended into the circular waveguide a distance X_i .

Figure 4 shows the simulated S_{11} as a function of the distance that the center conductor protrudes into the circular waveguide. A minimum value of $S_{11} = -12.7$ dB is predicted at $X_i = 9$ mm. While microwave energy is launched with reasonable efficiency, Figure 5 shows that the desired mode is not obtained. In this figure we plot the z component of the electric field at two different planes in the cylindrical

waveguide. Comparison with the analytically determined mode shapes shows that this is the TM_{01} mode.

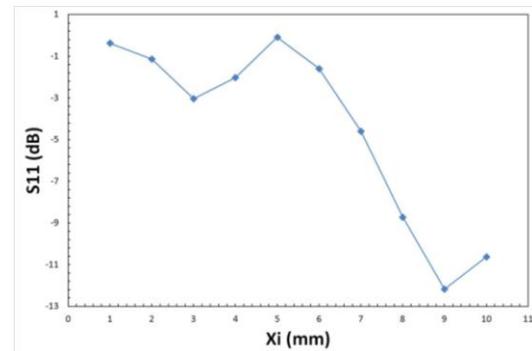


Figure 4. S_{11} as a function of protrusion of the center conductor for the axial-fed launcher.

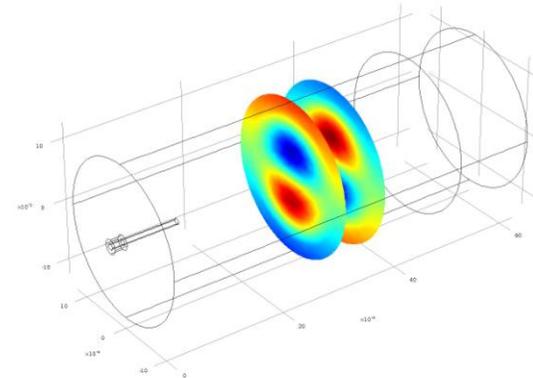


Figure 5. Axial launcher- z component of the electric field plotted at two planes in the cylindrical waveguide.

4.2 Side-excited launcher

We next considered an edge-excited launcher (Figure 6) where the coaxial line penetrates the cylindrical waveguide from the side. There are two design parameters, the distance X_i that the center conductor extends into the cylindrical waveguide, and the distance d from the center of the conductor to the back wall. We varied these two parameters over the range from 2 to 10 mm. While efficient launch of microwave energy was predicted, once again the desired mode was not obtained. Figure 6 shows the z component of the electric field in the cylindrical waveguide.

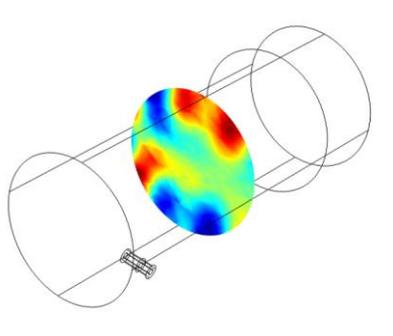


Figure 6. Edge-excited launcher: z component of the electrical field at a plane in the circular waveguide.

4.3 Tapered launcher

We now consider a tapered transition between a rectangular and a cylindrical waveguide (Figure 7). The motivation for this design comes from the observation that the desired TE_{11} mode has a nearly uniform electric field across the center of the cylindrical waveguide. A rectangular waveguide also has a nearly uniform electric field between top and bottom. A tapered transition should provide efficient coupling between the two regions. Finally, it is well known that an efficient transition between a coaxial transmission line and a rectangular waveguide can be made using a probe on the bottom surface of the rectangular waveguide. (In the simulated design the entire launcher is alumina so the coaxial to rectangular waveguide transition is smaller than typical for waveguides in air.)

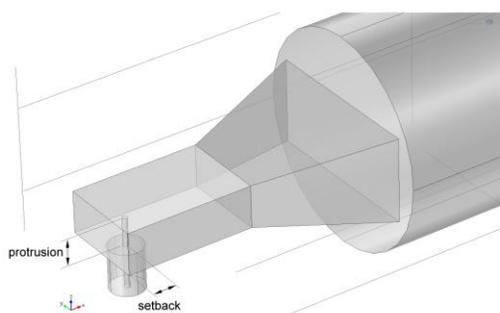


Figure 7. Tapered launcher consisting of a coaxial to rectangular waveguide transition followed by a tapered rectangular waveguide.

For a fixed taper length of 15 mm, the protrusion and setback were varied in order to determine the optimum values. This was conveniently done using two parameter sweeps. The optimum values were 3.1 mm for the protrusion and setback, yielding $S_{11} = -29$ dB. With this optimum design, the TE_{11} mode is launched as show in Figure 8 where we plot the x component of the electric field.

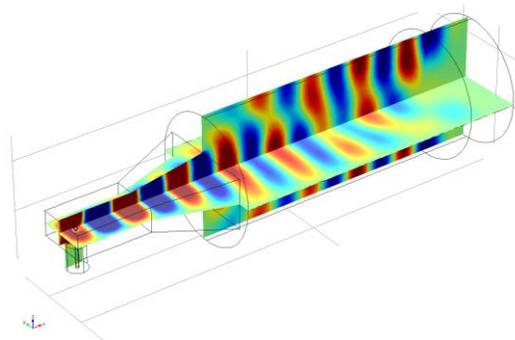


Figure 8. Tapered launcher- plot of x component of the electric field.

Finally we consider the effect of varying the taper length. Figure 9 shows the effect of varying the taper length from 5 mm to 25 mm. It is interesting that we see a periodic variation in S_{11} , clearly a result of interference between the reflected waves at the rectangular- taper and taper- circular waveguide transitions.

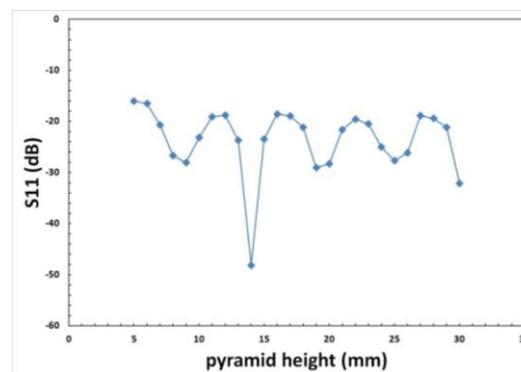


Figure 9. S_{11} as a function of taper length.

5. Summary and Conclusions

We have applied finite element simulation with COMSOL to the design of a launcher for a microwave Doppler flowmeter. The TE_{11} mode

is desired for efficient launching from the circular waveguide into the flow region. Of three different designs, a taper launcher is best for efficiently coupling microwave energy from a coaxial line to the circular waveguide.

6. References

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7. Acknowledgements

As part of the National Energy Technology Laboratory's Regional University Alliance (NETL-RUA), a collaborative initiative of the NETL, this technical effort was performed under the RES contract DE-FE0004000. This project was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government, through a support contract with URS Energy & Construction, Inc. and is part of the Industrial Carbon Management Initiative project. Neither the United States Government nor any agency thereof, nor any of their employees, nor URS Energy & Construction, Inc., nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

8. Appendix- settings for boundary mode analysis

Boundary mode analysis is used when it is necessary to launch a particular wave mode at a port. If the port is coaxial or rectangular then analytic solutions are straightforward and can be directly selected without performing boundary mode analysis. However if the port has any other shape the mode shape must be calculated numerically. In general there are many possible modes so for a particular simulation we need to select the mode of interest. The settings required in order to accomplish this choice in boundary mode analysis are confusing. Here we will clarify how to use these settings. In the present example the port is the entrance port for a 2.54 cm diameter alumina dielectric waveguide to be operated at 10 GHz.

Suppose we perform boundary mode analysis and we are not sure which mode is the one of interest. We therefore choose a number larger than one (in this example, 10) in the box **Desired number of modes**. We can choose to search for modes specified by either **out-of-plane wavenumber** or **effective mode index**. In microwave problems the first is the more natural choice. Then we need to make an entry in the box labeled **Search for modes around**. When modes are specified by wavenumber the entry in this box is in units of inverse meters. The wavenumbers will be of the order of the plane-wave wavenumber in the medium of interest. In the example here the medium has relative permittivity of 9 and consequently the plane-wave wavenumber is $2\pi f/c \sim 628 \text{ m}^{-1}$ at 10 GHz. The final setting is the frequency at which the analysis is to be performed. Typically boundary mode analysis is immediately followed by a solution of the electromagnetics problem in the entire domain (frequency domain analysis). Thus there are two steps to the study, boundary mode analysis (yielding saved solution 2) and frequency domain analysis (saved solution 1).

We focus now on identifying and specifying a particular mode. After performing both analyses, under **Results** there is a unique solution labeled solution 1 that can be plotted in the entire geometry. But which wavenumber

does this solution correspond to? Under solution 2 we see that there were 10 different values of the out-of-plane wavenumber. However none of these solutions can be plotted in the simulated geometry! So how can we find out which is the right one?

The solutions to the boundary mode analysis cannot be plotted on a 3D plot of the simulated geometry for two reasons: (1) the boundary mode solution only exists on the 2D surface of the port; and (2) the variable names for boundary mode analysis are different. (The variable names for electric field in the boundary mode analysis are mod1.emw.tEbmlx , mod1.emw.tEbml y , and mod1.emw.tEbmlz for the x , y , and z components, respectively.)

The steps in plotting a boundary mode solution are as follows:

1. Under the Data Sets node, create an entry Surface 1. Under Settings select Solution 2 and then select the boundary that corresponds to the port.
2. Under Results create a 2D Plot Group and then create a Surface plot.
3. In the settings for the Surface plot select Surface 1 as the data set. Enter one of the electric field variable names into the box Expression. Finally, select the wavenumber of interest and plot.

An example output showing some of the settings is presented in Figure 10.

So which of the boundary mode solutions does COMSOL use in the subsequent frequency domain analysis? We find that the lowest out-of-plane wavenumber solution is almost always the one that is used for frequency domain analysis. (The exceptions noted were when there were two very closely spaced modes). So once the correct mode has been identified, the settings for boundary mode analysis should be changed to one mode, with the entry in the box for the out-of-plane wavenumber slightly larger than the wavenumber for the mode of interest and less than any other mode.

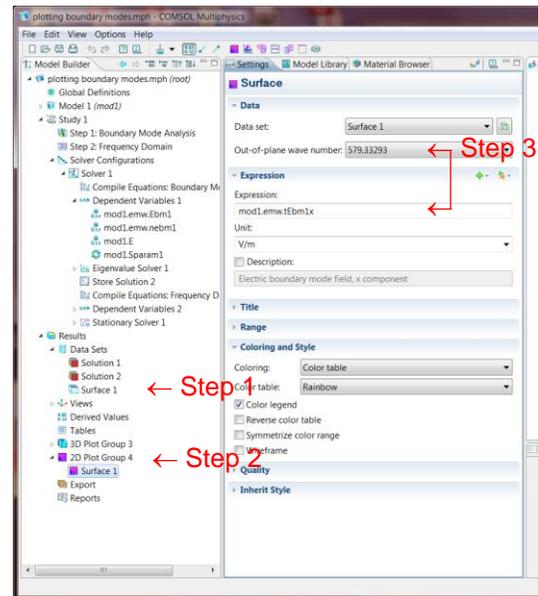


Figure 10. Settings used to obtain a plot of the boundary mode field.

If the port is a square or a circle the modes will often occur in degenerate pairs. If the remainder of the geometry is not symmetric there will be different results depending on which of the degenerate modes is launched. In order to select a particular mode it is then necessary to break the symmetry to split the two modes. When this is done each mode can be selected individually for simulation.