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Analyzing the Effect of Mesh Iterations on the Accuracy of Reflection Loss in Microwave Applications Using the Finite Element Method

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ABSTRACT

The aim of this research is to evaluate the performance of mesh iteration to ascertain the best iteration magnitude for electromagnetic characterization using the finite element method. In this work, COMSOL software is used to determine the transmission and reflection coefficients of the closed T/R rectangular waveguide with a sample of 15 mm thick PTFE placed inside the waveguide. The calculated scattering parameter provides information about how the material transmits and reflects microwaves. The calculated reflection coefficients are subsequently used to deduce the reflection loss (dB). The findings showed that the best mesh parameter for the transmission and reflection coefficients was a fine mesh with values of 0.9999 and 0.003, respectively. Further evaluation indicated that increasing the number of element iterations led to improved reflection loss. The most accurate reflection loss was achieved using an iteration of 24,372, which yielded a reflection loss of -52.52 dB. The lowest iteration was able to produce a reflection loss of -4.97 dB. From the electric field intensity, it was observed that the highest mesh had the minimum transmission intensity of 2389.5 v/m, while the highest transmission intensity was recorded for the 1167 mesh iteration.The results confirmed that the accuracy of the reflection loss and transmitted intensity is dependent on the magnitude of iteration used in the simulation. It is thus concluded that for better computational electromagnetics, higher iteration values should be used.

Keywords: Mesh iteration, Finite element method, Reflection loss, Microwave

I. INTRODUCTION

Computational methods should accurately and efficiently compute scattering parameters, reflection loss, attenuation, electric field and other microwave properties easily. However, proper understanding of the mesh iteration technique used for computing has been a challenge since no prescription iterations have been given for microwave computation analysis. This dearth of knowledge has caused research results to return different results based on the iterations used. In this work, the finite element method is used to investigate the best mesh iteration for computational electromagnetics. The finite element method (FEM) solution technique is used in the calculation of the full 3-D electromagnetic field of structures. The FEM analysis involves discretizing elements into finite numbers, obtaining governing equations for finite elements, assembling all the elements in the solution region, and solving the systems of equations obtained (Yakubu et al., 2021). During the division of the solution region, the region is divided into four non-overlapping elements with seven nodes. The approximate potential (Ve) within an element for the whole region is given as

$$\propto_1 = \frac{1}{2A}\left[(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y\right] \quad (1)$$

$$\propto_2 = \frac{1}{2A}\left[(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y\right] \quad (2)$$

Studying convergence requires choosing an appropriate mesh refinement metric. This metric can be either local or global. That is, the metric can be defined at one location in the model or as the integral of the fields over the entire model space. When choosing a metric, it is important to remember that different metrics will have different convergence behaviors. These meshes differ in terms of the element size and are compared in terms of the number of degrees of freedom (DOFs) within the model. The DOF is related to the number of nodes, the computational points that define the shape of each finite element (Falla et al., 2023). The computational resources required to solve an FEA model that are directly related to the number of DOFs are vital in computational electromagnetics (Wu et al., 2023).

The interaction of materials with electromagnetic fields is influenced by the inherent properties of the materials being interacted with. The outcome of the interaction may result in reflection of the waves, absorption of the wave or transmission of the wave or sometimes the combination of the three. One crucial point of the FEM is the discretization of the physical domain, and this procedure is called meshing. A well-designed mesh is necessary to achieve accurate results with acceptable computational effort (Alessandro et al., 2019).

In their study, Islán et al. (2019)investigated and simulated the behavior of the glenohumeral joint and the rotator cuff of a musician during his workout in repetitive routines with the use of FEM. They used an FEM approach to investigate the loading behavior of a human shoulder by including the ligament capsule in the anatomical model. They also obtained an improvement in the meshing process of the 3D model of human articulation by using a tetrahedron with 10 nodes as the mesh elements.

The scattering parameters S_{11} and S_{21} can be calculated from the reflection and transmission coefficients using signal flow graph analysis as previously reported (Yakubu et al., 2020):

$$S_{11} = S_{22} = \frac{\gamma(1 - Z^2)}{1 - \gamma^2 Z^2} \quad (3)$$

$$S_{21} = S_{12} = \frac{Z(1 - \gamma^2)}{1 - \gamma^2 Z^2} \quad (4)$$

where

$$\gamma = \frac{Z_s - Z_0}{Z_s + Z_0} \qquad (5)$$

$$Z = -j\mathrm{esp}(\gamma l) \qquad (6)$$

where Z_s, Z_0, l and $\gamma$are the characteristic impedance of the measurement system, input impedance, sample length and propagation constant, respectively.

For the simulation, the solution time to calculate S_{11} and S_{21} using COMSOL is strongly influenced by mesh properties such as geometric conformity, mesh density and element quality. A sufficient approximation of the problem domain is required for the geometric conformity of the area defined by the mesh elements. Minimization of the discretization error and realization of accurate solutions can be assured by having a mesh with density and size that are sufficiently high and small, respectively (Yakubu et al., 2021).

Methodology (FEM simulation)

The first step in our work was to calculate the values of S_{11} and S_{21} using COMSOL software version 4.5b. In the case of simulation, the radiation is simulated in two ways. In the first case, the wave equation was integrated through the radiation boundary box in the finite element simulator. Second, the reflection loss and electric field were calculated from the transmitted coefficients. The wave equation in (7) was used (Chung & Pun, 2020):

$$\nabla \mathrm{x}(\mu_r^{-1} \nabla \mathrm{x} E_z) - \left(\varepsilon_r - j\frac{\sigma}{w\varepsilon_0}\right) k_0^2 E_z = 0 \qquad (7)$$

where μ_r is the relative permeability, k_o is the free pace wavenumber, j is the imaginary unit, σ is the conductivity, w is the angular frequency, ε_r is the relative permittivity and εo is the permittivity of air.

In the COMSOL environment, the work is designed in the 3D work plane before going into the RF module where the electromagnetic wave is selected for harmonic waves. When all the parameters have been correctly assigned, a rectangular waveguide with a 15 mm thick PTFE substrate is simulated for the different mesh iterations. The results of the transmission coefficients, reflection loss and electric field at 8 to 12 GHz are presented. The principal material used in this study was COMSOL MultiPhysics Software. The manufacturing values for the complex permittivity, permeability and other microwave properties of PTFE (Teflon) were used. Details of the PTFE properties are given in Table 1 (Yakubu et al., 2024).

Table 1: Details of the PTFE Properties

S/N	Thickness (mm)	Complex permittivity	Permeability	Conductivity (W/m.K)
1	15.0	2.01-j*0.003	1.0	0.301

The waveguide that was simulated was 20 cm long, while the port of the waveguide was 2.228 cm by 1.143 cm long. The transmission and reflection coefficients and reflection loss were subsequently calculated using the software.

II. RESULTS AND DISCUSSION

A convergence test was carried out for the predefined meshes in the software to determine the best mesh for electromagnetic profiling. Figures 1 and 2 show the results of the reflection coefficient and transmission coefficient, respectively, for the predefined parameters. The reflection coefficients for the different predefined parameters for an empty rectangular waveguide. The results obtained clearly show that the accuracy of the predefined parameter varies with respect to the simulation. The findings showed that the best reflection coefficient was obtained for the extremely fine parameter, with an average value of 0.003, while the worst fit was obtained for the extra fine mesh, with an average value of 0.069, which is in agreement with the findings of (Boulvert et al., 2022). As expected, the average value of the reflection coefficient should equal zero for an empty rectangular waveguide.

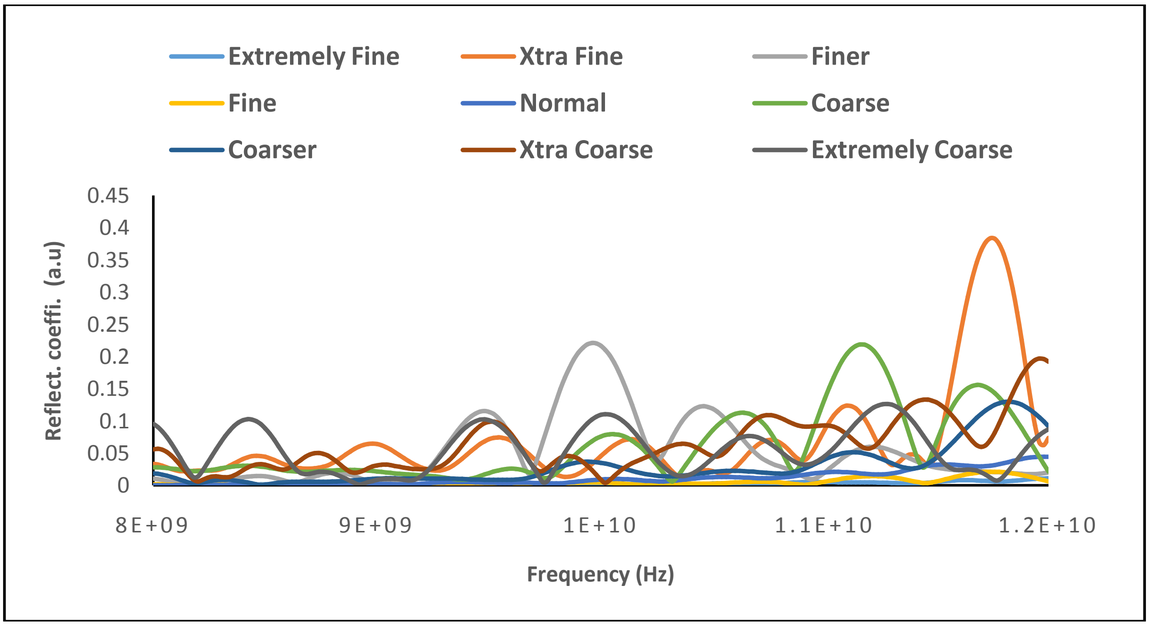


Figure 1: Reflection coefficients for empty RWG for different mesh parameters

In the same vein, Figure 2 depicts the behavior of the solver parameter for computation of the transmission coefficient, where the fine mesh type was the most suitable for transmission coefficient computation. For the empty waveguide, the best predefined mesh parameter is the fine mesh, for which the average value is 0.9999, which is in agreement with previous reports (Yakubu et al., 2022a). As expected, the value of the transmission coefficient for an empty rectangular waveguide is unity (one).

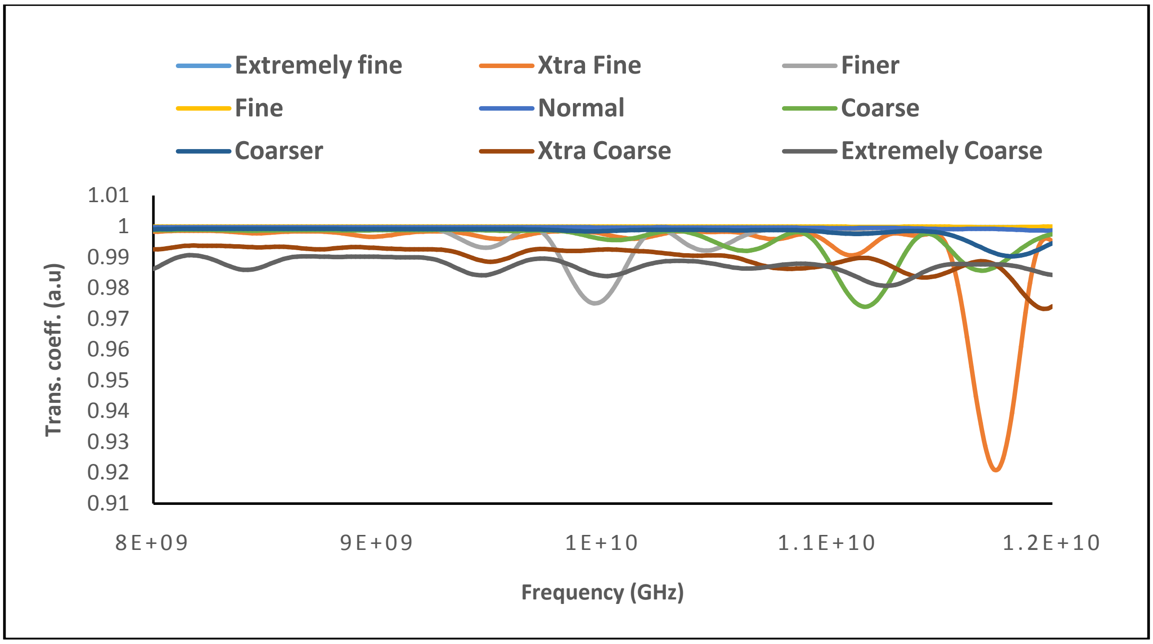


Figure 2: Transmission coefficients for empty RWG for different mesh parameters

For brevity, the average values of the transmission and reflection coefficients as a result of the different mesh iterations are summarized in Table 2. The results clearly show that the highest mesh iteration had the closest value to the manufacturer value for both the transmission and reflection coefficients. This affirms the postulate that high mesh iteration yields better results. This sequence of the values obtained is in agreement with reports that state that better convergence of the numerical solution will increase the computing accuracy (Ruggiero et al., 2019).

Table 2: Average Transmission and Reflection Coefficients

S/N	Elements	S_{21}	S_{11}
Mesh 1	24372	0.9397	0.2975
Mesh 2	8599	0.9395	0.2976
Mesh 3	3020	0.9389	0.2973
Mesh 4	1167	0.9285	0.3187
Mesh 5	456	0.8827	0.4322
Manufacturer Value		**0.9797**	**0.2778**
Yakubu et al., 2014		0.9395	0.2976

Careful observation of Figure 3 shows that the highest calculated reflection loss was -52.52 dB at 8.5 GHz for the 15 mm thick PTFE sample. The results showed that simulation iterations performed at higher element densities produce better reflection loss. These results are in close agreement with the manufacturer's values and with the results obtained for organic materialrefection loss, where Yakubu et al. (2022b) reported a loss of -12.6 dB and Ahmad et al. (2016) reported an attenuation value of -23.5 dB for a perfectly meshed rectangular waveguide. It is thus concluded that the size of the elements in the mesh plays a crucial role in accurately capturing the features of the electromagnetic problem.

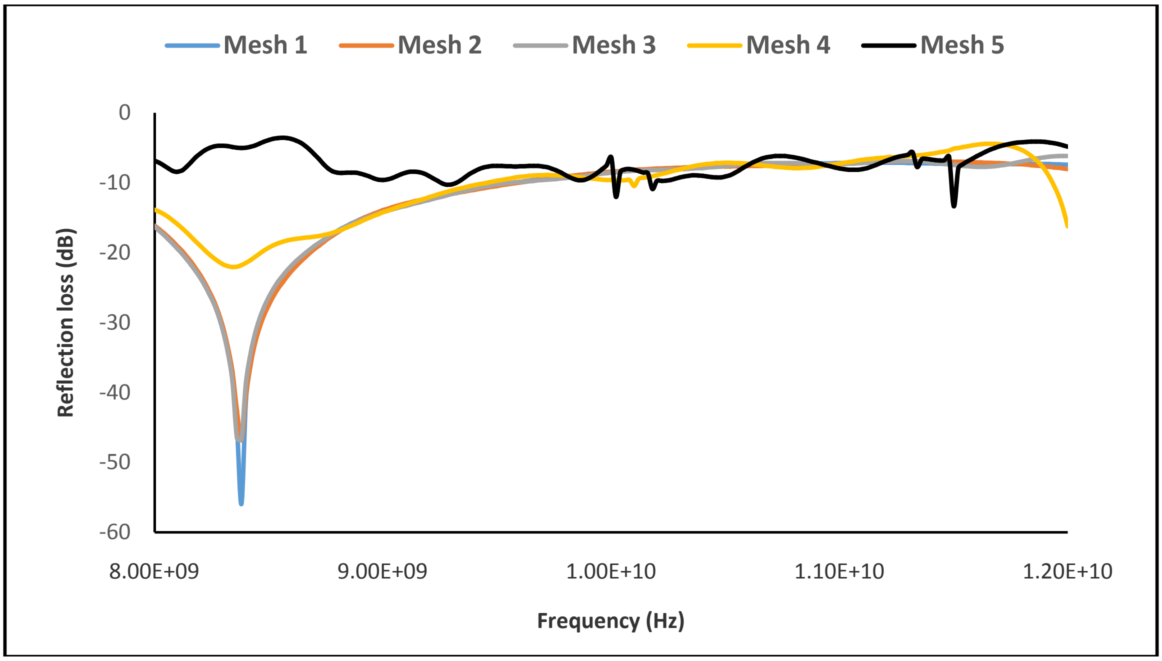
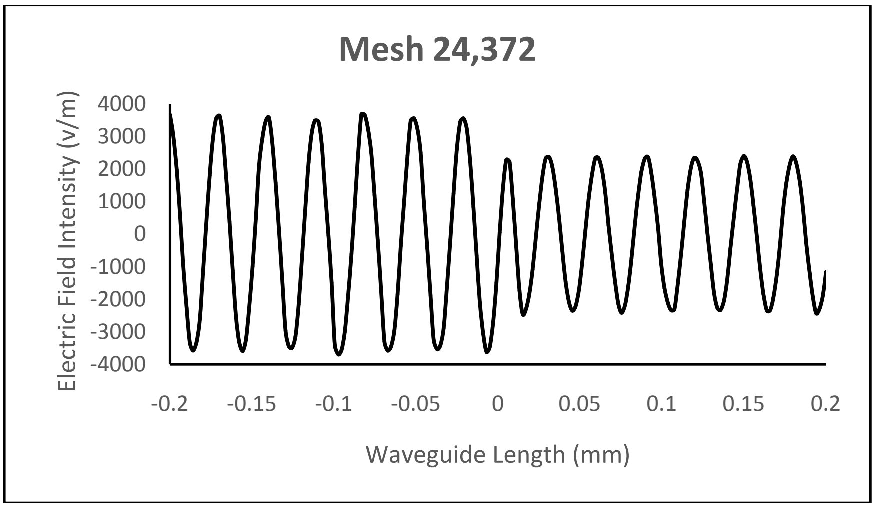


Figure 3: Reflection Loss for Different Mesh Elements

Table 3 shows a summary of the compared reflection loss for the different mesh iterations. The findings clearly show that the highest mesh iteration had the best loss compared to the manufacturer value, while the worst loss was obtained for the least mesh iteration.

Table 3: Comparison of Reflection Losses

S/N	Elements	RL (dB)
Mesh 1	24372	-52.52
Mesh 2	8599	-52.19
Mesh 3	3020	-43.13
Mesh 4	1167	-22.92
Mesh 5	456	-4.97
Manufacturer Value		**-55.25**
Yakubu et al., 2014		-52.20



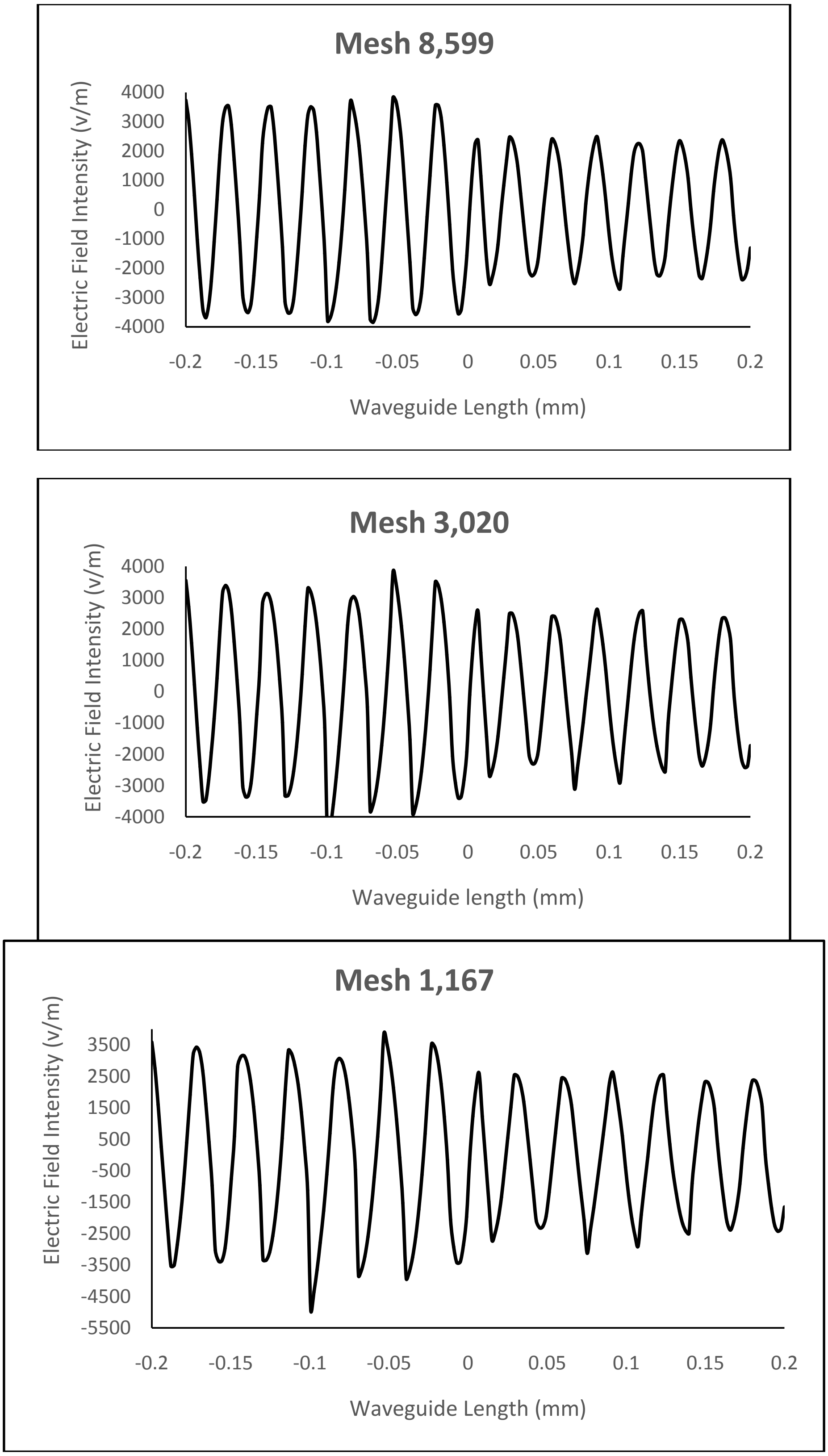


Figure 4: Electric field intensity for different mesh iterations

Table 4: Highest Transmitted Intensity

S/N	Elements	EF (v/m)
Mesh 1	24372	2389.5
Mesh 2	8599	2489.5
Mesh 3	3020	2632.4
Mesh 4	1167	2635.6

Figure 4 shows that the electric field intensity is influenced by the number of mesh iterations used in the simulation. The highest mesh had a minimum transmission intensity of 2389.5 v/m, while the highest transmission intensity was for the 1167 mesh iteration. Table 4 shows a summary of the maximum transmitted intensity for each iteration.

In conclusion, the findings indicated that the accuracy of the meshes used in the simulation has a significant impact on the simulation of the electromagnetic properties. Fine mash generally provides the best result among all the predefined parameters. The reflection coefficient for an empty waveguide should ideally be zero. The results presented confirm the suitability of the fine mesh for computational electromagnetics. As the number of mesh elements increased, the accuracy of the calculation improved. A mesh with 24,372 elements provided values that are in agreement with the manufacturer's values. It is thus postulated that for electromagnetic computations, a fine mesh parameter and high mesh density iteration should be employed when carrying out simulations.

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