# Multiphysics Simulation of Temperature Profiles in a Triple-Layer Model of a Microwave Heat Exchanger

**A.A. Mohekar, J.M. Gaone, B.S. Tilley, and V.V. Yakovlev**

Worcester Polytechnic Institute, Worcester, MA, USA

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## INTRODUCTION

Conventional applications of microwave (MW) heating systems include food processing, microwave assisted chemistry, high temperature treatment of materials, etc. [1], [2]. Relatively new devices are MW heat exchangers (MHE), which are used in solar energy collectors [3], power beaming applications [4], and MW thermal thrusters [5]. Working principle of the MHE is governed by coupling between electromagnetic, heat transfer, and fluid flow phenomena, and thus require particularly extensive experimental developments. This raises demand on multiphysics models that are capable of adequately simulating all essential effects occurring in MHEs.

Heat generation in a ceramic material undergoing MW heating is dependent on the electrical conductivity, which often increases exponentially with temperature [6]. Such nonlinear coupling results may lead to thermal runaway. A mathematical model for a single lossy layer [7] describes thermal runaway with the help of a power response curve (also called *S*-curve because of its shape). It determines steady state temperature of the lossy layer as a multivalued function of the incident power. Recently, a model of a triple layer laminate mimicking a MHE [8] has shown that for particular values of the layer width and complex permittivity, the *S*-curve acquires another (third) stable branch and becomes the *SS*-curve. This work has demonstrated a possibility of operating within controllable temperatures so that MW energy can be harnessed in form of heat energy. A 2D numerical model capturing the appearance of the *SS*-curve has been described in [9]. It showed that efficiency of a MHE increases when thermal runaway is achieved. Yet, the behavior of temperature fields under different operating conditions remains insufficiently understood.

In this paper, we extend the approach of [8], [9] by introducing a hydrodynamically fully developed Poiseuille flow in fluid carrying channels. We present the steady-state temperature profiles in the three-layer laminate that correspond to different lengths of the channels. Since steady-state temperature profiles depend on operating conditions, geometry and material parameters, we show how temperature profile in a triple-layer laminate varies with the length of the channel.

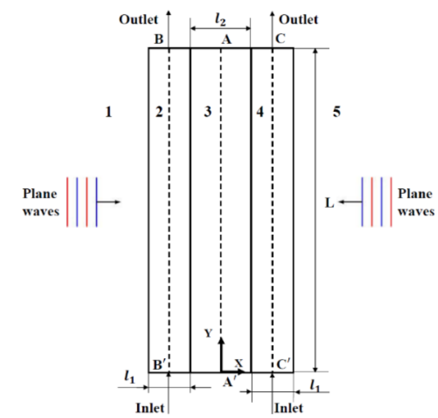


Figure 1. Triple-layered geometry subjected to symmetric MW irradiation; media 1 and 5 are free space, media 2 and 4 are lossless fluid, and medium 3 is lossy dielectric; $L$ is the length of channels.

## NUMERICAL MODEL

We consider a triple-layered geometry shown in Figure 1. We construct a numerical model in *COMSOL Multiphysics* capable of solving a coupled system of Helmholtz's, heat, and Navier-Stokes equations:

$$\nabla^2 \vec{E}_j + k_0^2 \mu_{rj} \left( \epsilon'_{rj} - i \frac{\sigma_j(T_j)}{\omega \epsilon_0} \right) \vec{E_j} = 0,$$

$$\rho_j C_{pj} \left( \frac{\partial T_j}{\partial t} + \vec{u_j}. \nabla T_j \right) = K_j \nabla^2 T_j + \sigma_j(T_j) \left| \vec{E_j} \right|^2,$$

$$\frac{\partial \vec{u}_j}{\partial t} + \vec{u_j}. \nabla \vec{u}_j = -\frac{\nabla P_j}{\rho_j} + \nu_j \nabla^2 \vec{u}_j, \; \nabla. \vec{u_j} = 0,$$

where $\vec{E}$ is electric field, $k_0$ is wave number of free space, $\mu_r$ and $\epsilon_r$ are relative permeability and permittivity respectively, $T$ is temperature, $\sigma(T)$ is temperature dependent electrical conductivity, $\omega$ is angular frequency, $\epsilon_0$ is permittivity of free space, $\rho$ is density, $C_p$ is specific heat capacity, $\vec{u}$ is velocity of fluid, $K$ is thermal conductivity, $P$ is pressure, and $\nu$ is kinematic viscosity. Subscript $j$ represents region of the solution.

Top and bottom boundaries of region 3 are assumed to be thermally insulated. Pressure and temperature at the inlet in regions 2 and 4 is 0.5 Pa at 300 K respectively, and the outlet in regions 2 and 4 was thermally insulated and maintained at zero pressure. No slip conditions are applied at external boundaries of channels 2 and 4. Boundaries between regions 1 and 2, 4 and 5 are exposed to ambient temperature of 300 K with heat transfer coefficient of 12.6 $W/m^2K$ undergoing Newton's law of cooling. In order to neglect fringe effect at the corners of the geometry, we set normal component of gradient of the electric field to be zero at the top and bottom boundaries of region 2, 3, and 4.

The developed COMSOL model was validated by comparing its 1D results for the case of no fluid flow with the output of the 1D mathematical model [8], [9]; corresponding power response curves were found to be in a satisfactory agreement. Dimensions were chosen accordingly to the criteria [8] so that the resonance occurs in the lossy layer, and material properties are taken from [9]; frequency of the incident wave is 2.45 GHz.

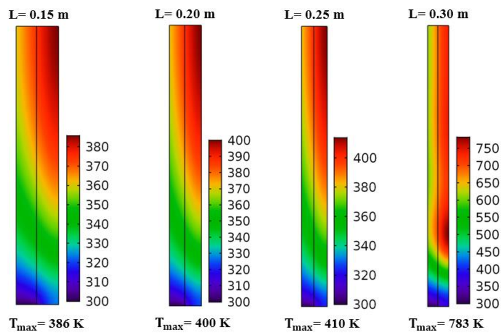


Figure 2. Three-layered scenario (Figure 1) with material parameters from [9]: steady-state temperature profiles for different lengths of the channel; incident power density 4,200 W/m$^2$.

## RESULTS AND DISCUSSION

The patterns in Figure 2 show that the maximum temperature $T_{\text{max}}$ increases with the length of the channel. As $T_{\text{max}}$ reaches a critical value, we observe a large increase in temperature due to thermal runaway. This suggests that high thermal efficiency can be obtained by appropriate length of the channel. As steady-state temperature profiles depend on operating conditions, geometry and material parameters, the presented model can help determine optimum design parameters of high-efficient triple-layered MHEs.

## ACKNOLWDGEMENT

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