Microwave Heating of Water in a Rectangular Waveguide: Validating EOF-Library Against COMSOL Multiphysics and Existing Data

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***Abstract* — EOF-Library, our open-source efficient coupler for Elmer FEM and OpenFOAM, is successfully validated against COMSOL Multiphysics, a commercial simulation package. We inform about discrepancies between our results and data from a series of research papers in the field. Simulations wherein microwaves are supplied to a water domain through a rectangular waveguide are used as benchmarks. The cases are conjugate problems involving fluid property dependence on temperature, microwave propagation and absorption, Marangoni effect and buoyancy-driven flow. We also report surface flow instabilities arising during prolonged microwave heating.**

Keywords* — *microwave heating, convection, EOF-Library, Elmer, OpenFOAM, COMSOL Multiphysics.

I. INTRODUCTION

Microwave (MW) heating of liquids is used in food industry (cooking, pasteurization, extraction) and chemical industry (microwave-assisted organic synthesis) [1,2]. Other prospective applications are currently in the research phase, such as oil/bitumen recovery from the ground [3]. In almost all cases MWs are used to accelerate heating, because they penetrate materials causing volumetric heating. Other common benefits of MW heating include safety and efficiency. Modelling MW heating of liquids involves solving Maxwell equations for electromagnetics (EM), Navier-Stokes equations for hydrodynamics (HD), combined with the heat transfer equation. Proprietary software package COMSOL Multiphysics is among those with out-of-the-box functionality for solving coupled EM and HD problems. On the open-source software side, we use EOF-Library [4]. The reason we seek open-source alternatives is that COMSOL is well suited for EM, but sometimes has convergence issues in HD problems, where it is also generally more difficult to configure for both necessary precision and acceptable solution time. For advection dominated transient fluid flows, especially highly turbulent ones, the finite volume method (FVM) has a reputation of being more robust and is used more frequently than FEM. Therefore, the common tool of choice is OpenFOAM (FVM). EOF-Library couples Elmer (FEM) and OpenFOAM simulation packages [5,6]. It enables accurate internal field interpolation and communication between the two frameworks. The coupling is based on the message passing interface (MPI) resulting in low latency, high data bandwidth and parallel scalability [4]. While EOF is a relatively new solution, it was already validated for magnetohydrodynamics (MHD) and plasma physics [7,8]. There are early developments for convective cooling of electrical devices with potential applications in electrical motors, flow sensors and transformers. To benchmark EOF, we choose a problem involving the heating an open (topside) water reservoir placed inside a vertically oriented rectangular waveguide with. MWs (2.45 GHz, TE 10 mode) are introduced at the inlet port at the top of the waveguide. Ratanadecho et al. measured temperature and compared readings with 2D simulations [9]. Water and NaCl-water solution were studied, considering the dependence of relative permittivity on temperature. This problem was studied experimentally and numerically for different liquids, MW heating power and system geometry [10–13]. Laminar flow regime was assumed, and Marangoni effect was accounted for. The physical picture is as follows. The incident wave reaches the free surface of water, where much of its energy is reflected and exits the computational domain through the inlet port. The transmitted wave penetrates and heats water, inducing buoyancy-driven flow. Waveguide walls are assumed fully reflective and the water reservoir is fully transparent (0.75 mm thick polypropylene walls). The EM problem is solved for air and water domains, while the heat and mass transfer problem are solved for water only. The reservoir is considered a thermal insulator, so heat is lost through the free water surface only. OpenFOAM is not equipped with 2D solvers, so a 3D geometry with a structured mesh in the x-z plane and 1 element extrusion in the y direction was defined, which is equivalent to a 2D problem if one enforces symmetry conditions on extrusion faces.

II. RESULTS

We replicated the case described in [11,12] – the Boussinesq approximation was used and Marangoni effect at the free surface of water was considered. Default MW power is 300 W (we also use 500 W to verify the results from [13]) and initial water temperature is 28 °C. Water properties are taken from [11]. For benchmarks, the first 60 seconds of the heating process were simulated. We found that EOF and COMSOL solutions are in very good agreement throughout the series of benchmark tests, as seen in Figures 1 and 2. However, both experiments and simulations by [9-13] were in stark contrast with our own findings – an example of this is shown in Figure 2b, where it is evident that experiments and simulations do not agree for [11,12]. If fact, we found that thermal camera images from [11] are contradictory and agree more with our current simulations than results in [11,12]. Weirdly enough, in Figure 2 one can see that the 500W case by Klinbun et al. indicates less generated heat than the 300W case. The agreement between EOF and COMSOL and the discrepancies between ours and reported results persisted when we chose 0 °C initial temperature, transitioned to the full buoyancy model, set all properties as temperature dependent and even set container walls as thermally conductive [14].

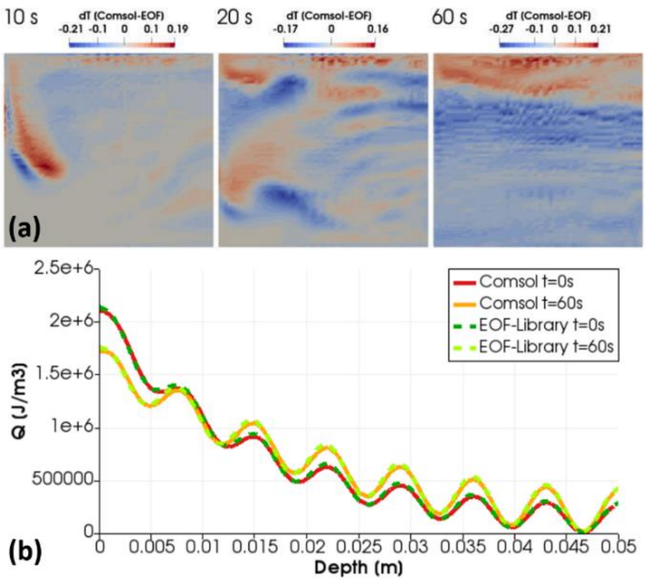

Figure 1. The difference between EOF-Library and COMSOL at different time stamps: (a) temperature field and (b) total dissipated power on container vertical axis at the beginning/end of the simulation.

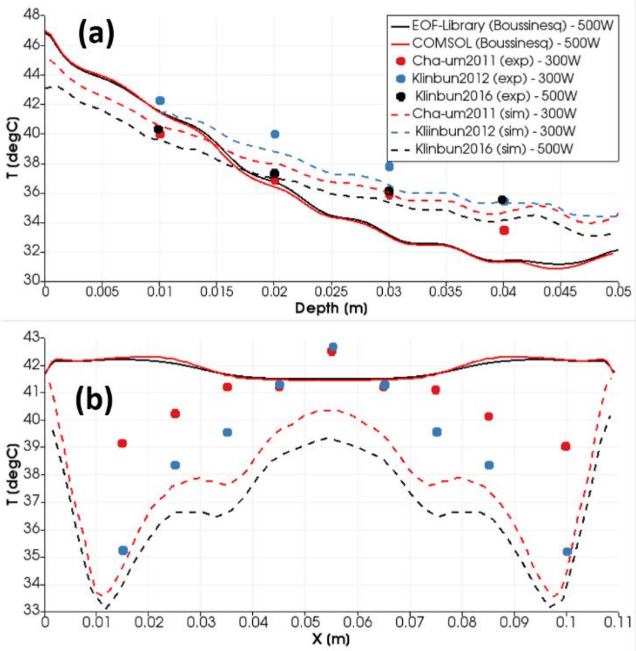

Figure 2. Temperature distribution along (a) the vertical axis and (b) the horizontal axis at 1 cm depth after 60 seconds of heating.

We suspect the issues might be due to errors in implementation or case setup in [9-13] – this is because the source cases are also rather inconsistently documented. Interestingly, extending the simulation duration to beyond 150 seconds reveals unexpected behavior – depending on the prescribed heat transfer coefficient for the free surface, surface velocity irregularities set in which then develop into pulse-like perturbations that propagate across the surface from the center of the reservoir surface. This results in sporadic velocity oscillations (Figure 3a) and symmetry breaking (Figure 3b). We are currently determining the nature of these instabilities, which, to our knowledge, have not been reported for MW heating problems of this type.

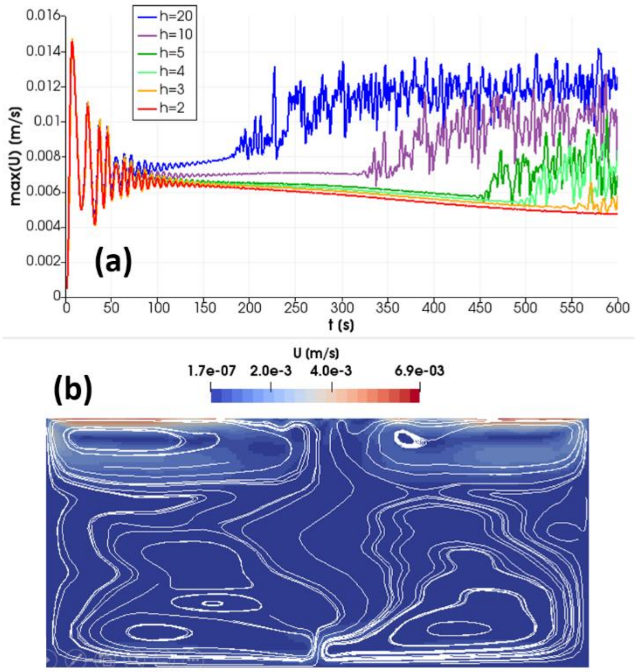

Figure 3. (a) Maximum velocity magnitude over time for different heat transfer coefficients (designated as h) and (b) velocity magnitude and streamlines for h = 5 W/(m^2·K) at 600 seconds of flow time.

References

[1] F.-G.C. Ekezie, D.-W. Sun, Z. Han and J.-H. Cheng, Trends Food Sci. Technol. 67 (2017)

[2] J.D. Moseley and C.O. Kappe, Green Chem. 13 (4) (2011)

[3] A. Bera and T. Babadagli, Appl. Energy 151 (2015)

[4] J. Vencels, P. Raback and V. Geza, SoftwareX 9 (2019)

[5] Ruokolainen, M. Malinen, P. Raback, T. Zwinger, A. Pursula and M. Byckling, Elmer solver manual, CSC–IT Center for Science.

[6] H.G. Weller, G. Tabor, H. Jasak and C. Fureby, Comput. Phys. 12 (6) (1998)

[7] J. Vencels, A. Jakovics and V. Geza, Magnetohydrodynamics 53 (4) (2017)

[8] M. Kubecka, A. Obrusnik, P. Zikan, M. Jilek Jr, J. Vencels and Z. Bonaventura, Preprint submitted to Surface and Coatings Technology

[9] P. Ratanadecho, K. Aoki and M. Akahori, Appl. Math. Model. 26 (3) (2002)

[10] W. Cha-um, P. Rattanadecho and W. Pakdee, Exp. Therm. Fluid Sci. 33 (3) (2009)

[11] W. Cha-um, P. Rattanadecho and W. Pakdee, Food Bioprocess Technol. 4 (4) (2011)

[12] W. Klinbun and P. Rattanadecho, Appl. Math. Model. 36 (2) (2012)

[13] W. Klinbun and P. Rattanadecho, Int. Commun. Heat Mass Transf. 70 (2016)

[14] Juris Vencels, Mihails Birjukovs, Juhani Kataja and Peter Raback, Case Stud. Therm. Eng. 15 (2019)