Multiphysics Approach of the Performance of a Domestic Oven

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Abstract: The heat and mass transfer processes occurring in a domestic oven is in detailed analyzed in this work, with the final objective of improving the global energy efficiency of the system. A 3D Finite Element model developed with a Multi-physics approach is compared and validated with the experimental data from the standard test for energy consumption of the European Union (EN 50304:2001). In this test a brick is heated till it reaches a determined temperature jump. The evolution of the experimental temperature distribution inside the brick is found to correlate well with the theoretical transient predictions. The prediction of the quantity of evaporated water is also found to be similar to the experimental value. The Multi-physics model created allows us to analyze the effect of innovative strategies to reduce the energy consumption and increase the energy efficiency on the oven behavior.

Keywords: Heat and mass transfer, Domestic Oven, Finite Elements Method, Multi-physics simulation.

1. Introduction

A deep knowledge of the heat and mass transfer processes occurring in a domestic oven is decisive in order to reduce its energy consumption. Therefore this research work falls within the Green Kitchen project, where different strategies are evaluated to reduce the use of energy within the domestic environment and increase the energy efficiency in the home appliance sector [1]. This project is financed by the European Union through the Seventh Framework Programme (via Marie Curie Actions: Industry Academia Partnership and Pathways program—IAPP). The partners of this project include three universities—University of Applied Sciences of Southern Switzerland (SUPSI) in Switzerland, Politecnico di Milano in Italy, and Wrocław University of Technology in Poland—and the home appliance company Whirlpool Corporation. The aim of the implemented research program is to develop and share crucial knowledge in the field of advanced technologies and eco-design strategies needed for drastically improving energy efficiency and resources utilization in the household environment. In this context, some of the activities of the project are focused to the development of innovative heat transfer models for cooking in ovens (Task T5.2 in Work Package 5). Several efforts [2-14] have been dedicated in the last years to investigate the heat transfer phenomena (conduction, convection and radiation) participating in the domestic ovens. However, further efforts are needed to reduce the energy consumption and increase the energy efficiency of these home appliances.

1.1 Objectives

The main objective of the present study is to perform numerical thermal analyses to improve the energy efficiency of the domestic ovens, and compare it to the experimental results in order to adjust the model. The development of the numerical model is created to improve the understanding of the heat transfer processes occurring during the oven operation. Then, new advances strategies to increase the energy received by the food load could be analyzed and optimized with this validated model. The results for the standard test for energy consumption of the European Union (EN 50304:2001) are selected as the reference case to be compared with the theoretical predictions.

2. Experimental Methodology

The standard test for energy consumption of the European Union (EN 50304:2001) [15], that is used to validate the numerical predictions is briefly described in the present section. In this test a wet brick representing the food sample is inserted in the geometric center of a domestic oven (see Figure 1) and it is heated from an initial temperature of 5±2°C until it reaches a determined temperature jump (55°C).

Figure 1. The oven and the position of the brick inside (Normative Oven Energy Class Test: EN 50304).

The brick temperature is monitored with thermocouples of type J (iron/constantan) that are recorder with a data logger (Yokowaga MV100) with a frequency of acquisition of one second. The weight of the brick decreases as it loses a certain amount of water by evaporation during the heating process.

3. Use of COMSOL Multiphysics®

The modeling of the multiple physics as heat and mass transfer occurring in an oven when heating a wet and cold food sample (brick) is performed using *Comsol Multiphysics®* [16]. A Finite Element 3D model of the heating and evaporation processes is developed using "Heat and Mass Transfer" and "Transport of Dilute Species" modules.

The main elements of oven system (oven structure and the brick, without physical representing the air in the cavity) are simulated resulting in a system of non-linear unsteady-state partial differential equations to be solved.

For the oven, radiation, convection and conduction [17] are included in the model as the main heat transfer processes. For the brick, the evolution of the moisture concentration is also modeled to illustrate the loss of moisture during the test (inside the brick, diffusive processes describe both heat transfer and moisture transport).

The study has been carried on using a time-dependent simulation to reproduce the time of the standard energy test which is usually 50 minutes.

3.1 Geometry and Mesh

The main elements of the oven are represented in a three dimensional geometry with the following classification:

-Three heating elements (broil, bake and ring).
-A front door composed of three glasses.
-The cavity frame.
-The baffle (fan cover).
-A solid element simulating the brick.
-An insulating enclosure which delimits the oven cavity.

A similar geometric representation between the model and the mechanic parts is reached when building the model, as can be seen in Figure 2. From the CAD simplified geometry of the oven the surface and volume meshes were generated using the pre-processor of the software. Mesh size was dense near the heating elements and the baffle structure, by using different types of finite elements depending on the volume to mesh. Mesh size (11.608 elements) for whole oven was optimized and finalized for the better accuracy and computational time.

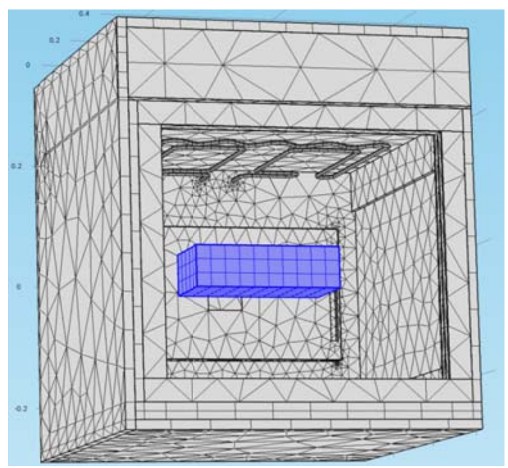

Figure 2. View of the Finite Element model grid with the brick (in blue) inside the cavity.

3.2 Boundary conditions

The Finite Elements Model is composed exclusively of solids parts. The main mechanism of heat transfer in the solids is considered to be the conduction. The coefficients for convective heat and moisture transfer to the surrounding air were obtained from another study [18], and are included as an input in the COMSOL model.

The heat transfer by radiation between surfaces is calculated using each surface temperature and the emissivity as an input data.

The experimental values of the temperatures of the heating elements (broil, bake and ring) and for the air inside the oven cavity are included as inputs in the model (measured experimentally). The initial temperature of the other elements, the initial moisture content of the air in the cavity and the selected oven function (static with a temperature set of 200°C) are also included as inputs in the model

3.3 Governing equations

The COMSOL Heat Transfer Module provides a combination of capabilities to model heat transfer via conduction, convection, and radiation, as well as the ability to couple these to other physics. In this study the physic coupled with the thermal exchange is the Transport of Dilute Species to study the mass transfer in the brick. The Heat Transfer Module mainly solves the energy equation as follow:

$$\rho C_P \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q \qquad (1)$$

where T (K) is the temperature, ρ (kg/m^3) is the density, C_P (J/kg·K) is the heat capacity at constant pressure, k (W/K·m) is the thermal conductivity and Q (W) is the thermal power.

On the other side, the Transport of Dilute Species module implements for each species considered the following mass balance equation:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D\nabla c) = R \qquad (2)$$

where c (mol/m^3) is the concentration of the species, D (m^2/s) denotes the diffusion coefficient and R (mol/s·m^3) is the reaction rate expression for the considered species.

4. Results

The Finite Elements Model provides the temperature evolution on all the elements of the oven and in the case of the brick the moisture concentration too. In this study their transient behavior is analyzed.

Figure 3 shows the predicted temperature surface plots, where it can be clearly seen that the broil reaches the maximum temperature, whereas the external walls are almost at ambient temperature.

The predictions of the transient evolution of the quantity of water evaporated from the brick and the brick moisture concentration, and the temperature profiles inside the brick correlate well with the experimental data obtained from the standard test for evaluating the energy consumption of a domestic oven.

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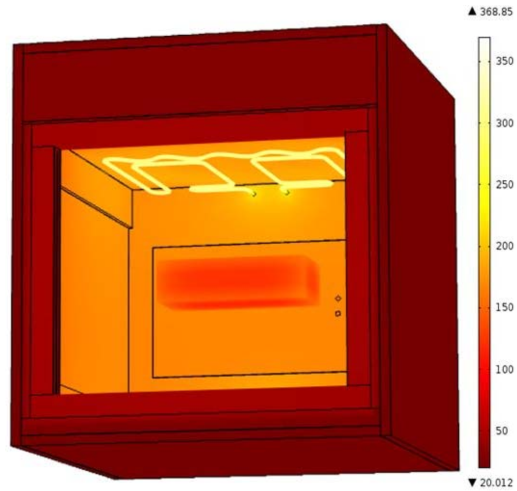

Figure 3. Predicted temperatures of the oven surfaces (color scale in °C).

One of the most interesting results from this simulation is the temperature behavior in the brick during the simulated test. Figure 4 shows the temperature field in three transversal brick sections obtained after 50 min at a cooking temperature set of 200°C.

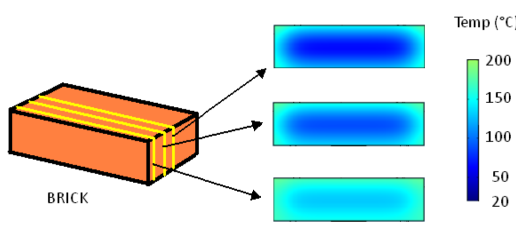

Figure 4. Predicted temperature profiles at different axial cuts of the brick.

In order to validate the numerical results obtained with the model, the evolution of the brick temperature has been compared with the experimental results of the standard energy consumption test.

Figure 5 shows how the experimental temperature into the brick increases over time and its comparison with the simulation results. This 3D model predicted quite well the brick temperature behavior during all the time necessary to reach the 55K differential temperature inside the brick.

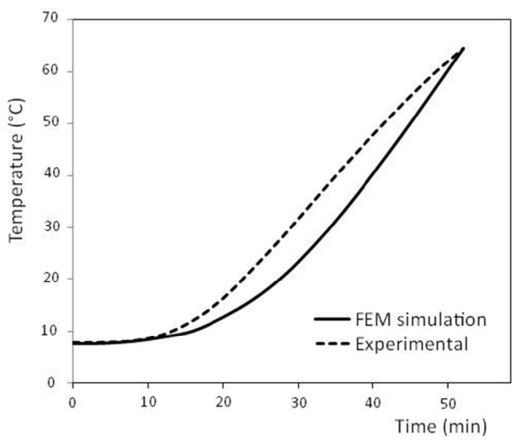

Figure 5. Evolution of the internal temperature of the brick: numerical and experimental results.

In Figure 6, the predicted values of moisture concentration at the brick surface at the end of the test are shown. As expected, the convective loss of moisture at the boundaries results in a lower moisture concentration at the corners of the brick compared to the concentration at the center of the faces.

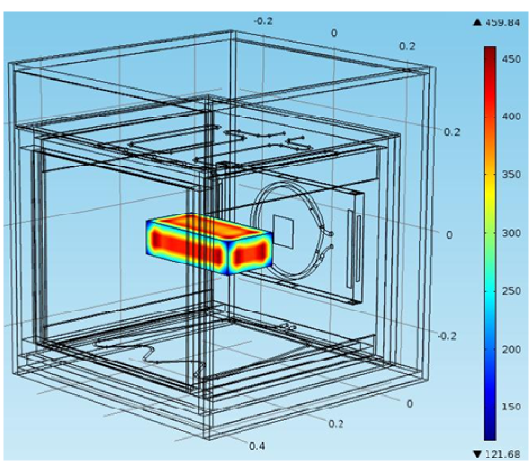

Figure 6. Brick surface moisture concentration (mol/m^3) at the end of the simulated test.

It is also interesting to determine how much moisture remains in the brick after the test (cooking). In this case, the numerical prediction (166g of water evaporated) correlates well with the experimental result (171g).

5. Conclusions

In this study a Finite Element Model developed in COMSOL Multiphysics and representing a domestic oven performance is experimentally validated. This model represents then a general and predictive tool capable to describe the real ovens behavior over a wide range of process and fluid-dynamic conditions, making possible to further study different strategies to reduce the energy consumption of an oven without decreasing the final quality of the cooked product.

Between the advantages of modeling the domestic oven with Finite Elements Methods it should be mentioned the option to use coupled physic models (as, for example, mass and thermal transport), the use of established boundary conditions or the possibility to estimate the prediction error.

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