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Three-dimensional numerical solution of heat transfer in a built-in domestic oven

Gabriel C. de Souza[1], Francisco A. A. Gomes[1], Thiago T. Freitas[2]

[1]*Department of Mechanical Engineering, Federal University of Technology - Paraná*
[2]*Department of Civil Engineering, Federal University of Technology - Paraná*
Via do Conhecimento, Km 1, Pato Branco, 85503-390, Paraná, Brazil
caberlim.gabriel@gmail.com, franciscogomes@utfpr.edu.br, thiagofreitas.engcivil@gmail.com

Abstract. It is widely observable nowadays the trend of the population, especially in more developed countries, towards the search for more efficient, safe, and with less environmental impact products and services. This trend is often reinforced by impositions from regulatory agencies that offer incentives to manufacturers to make their products better in these aspects. Domestic ovens are a type of durable consumer good and somewhat controversial in terms of efficiency and safety. Despite the current legislation that aims to guarantee a minimum of safety in the operation of domestic ovens, especially the most basic models, are still causing accidents, in particular, burns due to their geometry whose external surfaces can reach high temperatures due to the high dissipation of excess heat from the cooking process, resulting from fuel-burning or electrical resistors. The present study brings a three-dimensional and transient analysis of the heat transfer through the numerical solution of the finite volume method of a standard domestic oven. The analyzed model is based on a small built-in domestic oven, a liquefied petroleum gas burner, modeled as an insufflation of hot gas, a cavity partially covered by thermal insulation, and a door composed of a double glass window. From the temperature fields in the model, as well as flow speeds over the oven's operating time, a result is obtained that is indicative of the regions with the greatest energy loss, guiding possible improvements of the model for greater safety during its operation.

Keywords: Domestic Oven, Convection-Diffusion, Heat Transfer.

1 Introduction

Heat transfer problems are of great engineering interest since any unwanted transfer represents a loss, or in other words, an unnecessary expense. Therefore, it is always desirable to perform a thermal analysis of a product or process to minimize losses or to ensure that the heat transfer occurs in the desired way. According to Incropera [1], analytical solutions for these types of problems can become very difficult to make, thus requiring the search for other methods. The computational heat transfer together with computational fluid dynamics is a good alternative for problems with complex geometries, allowing a deep and satisfactory analysis through the numerical solution of discretized governing equations. Despite their origin in the aerospace industry, according to Moukalled et al. [2], today these tools are fundamental in all types of industry, from automotive to biomedical.

Domestic ovens are essential items in many houses, usually sold together with stoves, for the preparation of all types of food. These ovens consist of a cavity heated by an energy source, which can be electrical, through resistors or chemical through fuel burners, thus allowing the cavity to reach high temperatures and to cook meats, cakes, bread, etc. Due to the nature of its operation, legislation such as that of Instituto Nacional de Metrologia [3], for Brazil, is necessary to guarantee safety through a temperature limit on external surfaces of domestic ovens during their operation. Even so, especially in simpler models, the front door still reaches high temperatures, being a risk zone for burns, as temperatures above 44 degrees Celsius are already capable of degrading proteins and the damage to human tissues increases exponentially with temperature according to Marx et al. [4]. In this way, manufacturers and consumers have generated a demand for more efficient and safer products.

The study of heat transfer in ovens is a widely explored subject and in recent years it has been approached in several ways. Illés and Bakó [5] bring good results for the effects of flow and heat transfer through the numerical method for industrial process ovens; Abraham and Sparrow [6] developed a predictive model of heat transfer to a load inside an electric oven; Therdthai et al. [7] obtained data for the optimal preparation of bread in a commercial oven through a two-dimensional study using CFD; Mistry et al. [8] developed a transient CFD model of an electric oven capable of accurately representing temperature fields and cycles for baking food. Studies, such as those mentioned, demonstrate the effectiveness of computational and numerical methods in the analysis of heat transfer problems involving complex processes such as convection, radiation, turbulence models, and even combustion processes with chemical reactions in a domestic oven as done by Özdemir [9].

This work presents a numerical study of a built-in domestic oven, modeled in a simplified way with the main objective of evaluating the trends of heat loss during its operation. The analysis contemplates a volume of air external to the oven, considering the heat losses of the carcass to the environment, a configuration that, according to the authors' knowledge, had not yet been studied, thus considering all types of losses to the environment.

2 Physical Modeling

2.1 Governing Equations

To solve heat transfer and fluid dynamics problems, some equations must be defined for control volumes to guarantee the physical behavior of the problem. The Navier-Stokes equations are used to modeling this unsteady compressible fluid flow problem, under the hypothesis of continuum, Lamb [10]; Batchelor [11]. This set of equations are represented by the conservation of mass, Newton's $2nd$ law, and conservation of energy, Moukalled et al. [2], Blazek [12].

Conservation of the mass ensures that, for a control volume without sinks or sources, the mass will be conserved at a local level. Since **v** is velocity, ρ is density and t is time, this behavior, in the flux form, can be defined as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \mathbf{v}] = 0. \tag{1}$$

The Newton's $2nd$ law, for a volume of fluid, with p as pressure, μ the dynamic viscosity of the fluid and $\mathbf{f}_b$ a generic body force, can be defined as

$$\frac{\partial}{\partial t}[\rho \mathbf{v}] + \nabla \cdot \{\rho \mathbf{v}\mathbf{v}\} = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f}_b. \tag{2}$$

Energy conservation implies that, in a control volume, the energy balance must be equal to zero during a process given the absence of an internal energy source. This energy is maintained and can be transformed from chemical to mechanical, kinetic, and so on. With $\hat{h}$ being the specific enthalpy of the fluid, τ the viscous tension tensor, $\dot{q_V}$ the rate of heat source or withdrawal in the control volume per volume unit, and $\dot{q_s}$ the heat transfer rate per unit area over the surface of the control volume, the energy conservation equation in terms of the specific enthalpy can be defined as

$$\frac{\partial}{\partial t}(\rho \hat{h}) + \nabla \cdot [\rho \mathbf{v} \hat{h}] = -\nabla \cdot \dot{q_s} + \frac{Dp}{Dt} + (\tau : \nabla \mathbf{v}) + \dot{q_V}. \tag{3}$$

2.2 Domestic Oven Model and Geometry

The model used in the present work was based on the geometry of a small size built-in Brastemp brand stove with a combined oven. The main characteristics and dimensions of the model were maintained to obtain a result closer to reality. Metal sheets, which are part of the structure as well as the glass windows, however, had their thickness set to a standard 2.5 mm to reduce computational costs that thinner sheets would bring due to the need for thinner meshes. The geometry was designed using the commercial software Autodesk Inventor.

As shown in Fig. 1, the oven is composed of several types of materials such as steel in the housing, false bottom, and door frame; glass, inside and outside windows, and an insulating blanket that is in the region between the outer wall of the housing and the wall of the internal cavity. The regions of the internal cavity, extended environment, and door cavity are filled with air.

The oven has a hot air outlet at the top rear and two cold air inlets at the bottom. A plate with holes for air passage represents the false bottom that separates the cavity where the burner is located from the cavity in which the food is prepared. The door consists of a double glass window with an external and an internal window, fixed in a steel frame and separated by confined air. As the interest of this work is in the operation of the oven and the heat transfers in its regions, the components related to the stove were disregarded in the modeling.

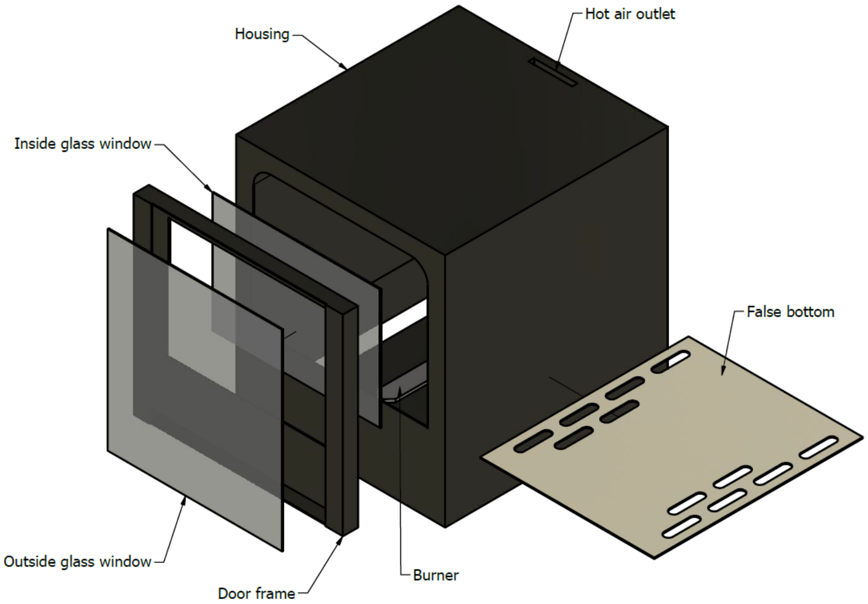


Figure 1. Built-in domestic oven model

2.3 Physical Properties

Thermophysical properties for each region were defined as constant, considered at $300K$, initial temperature of all the domain, despite being a function of temperature. Their values for each of the regions are described in Table 1, in SI units. The properties of steel and air were obtained from Incropera [1], while for glass and glass wool they were obtained from Engineering ToolBox [13], [14], and [15]. The air was modeled as a perfect gas.

3 Numerical Procedure

3.1 Finite Volume Method

The focus of the work is a numerical analysis of a domestic oven. For the numerical solution, the domain and the equations that govern the physical behavior of interest are discretized and, finally, resolved. The finite volume method was used in this work, which consists of discretizing the governing equations based on the division of the domain of interest in non-overlapping cells whose conservative equations are satisfied. This process results in algebraic equations that are usually solved numerically, according to Minkowycz et al. [16].

3.2 Mesh

For the domain discretization process, an unstructured mesh was generated from the geometry presented above. Through the open-source software SALOME, the geometry was imported and used to generate the three-dimensional mesh through the NETGEN algorithm. For post-processing, the open-source application ParaView was used, allowing visualization of the mesh and results.

Table 1. Properties of the materials

Region	Material	Property	Value
Housing	Steel AISI 1010	Thermal conductivity	63.9
False bottom		Density	7832
Door frame		Specific heat	434
Outside glass	Glass common	Thermal conductivity	1.05
Inside glass		Density	2500
		Specific heat	670
Insulation	Glass wool	Thermal conductivity	0.04
		Density	25
		Specific heat	840
Air	Air	Specific heat	1007
		Viscosity	184.6 e-7
		Prandtl number	0.707

To contemplate the volume of external air as well as the profile of heat exchange and airflow inside the oven and confined air in the door, these regions were also used in the generation of the mesh. The oven geometry was "immersed" in a semi-spherical domain with 4.2 meters in diameter. Regions such as the wall of the burner, the air inlets and outlets of the oven, and the components with small thickness have been configured for finer meshes to better match the geometry. As a result, the mesh obtained has 1.57 million tetrahedral cells. The Fig. 2 shows a lateral section of the mesh in half of the domain, allowing to identify the semi-spherical domain, oven door on the left, and the hot air outlet on the top on the right. The Fig. 3 brings a more detailed frontal cut also in the middle of the domain, this allows identifying the contours of the carcass as well as the region of the insulation, false bottom, and burner.

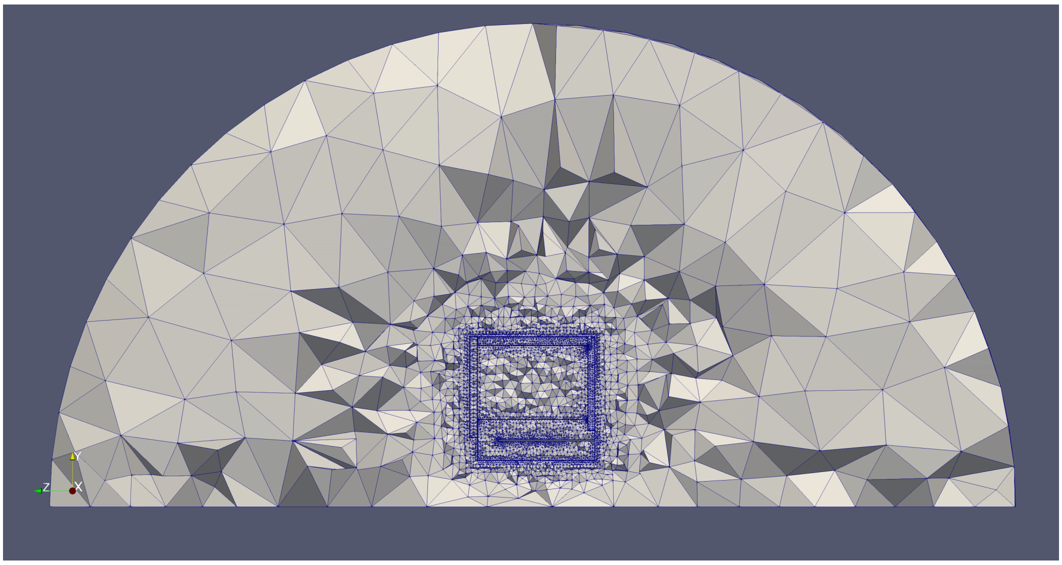


Figure 2. Lateral section of the computational domain

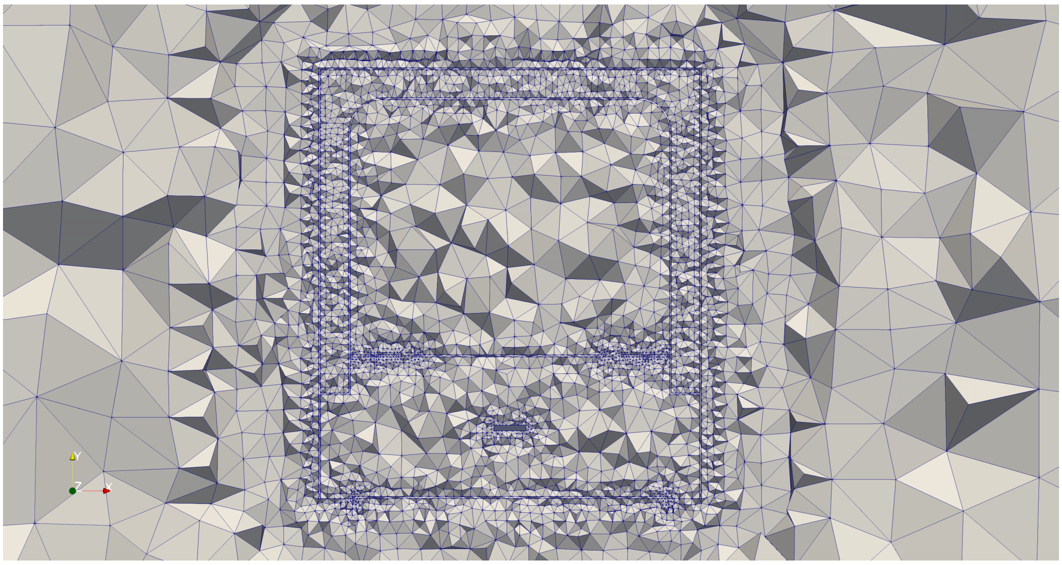


Figure 3. Frontal section of the computational domain

3.3 Boundary Conditions

For the domain boundaries, a wall condition was adopted for the straight face of the semi-sphere while a non-restrictive condition (inlet/outlet) was adopted for the curve, allowing the entry and exit of ambient air according to the need of the flow. The $300K$ temperature and zero fluid velocity were adopted as initial conditions for all regions.

Although its geometry is not part of the solution, the condition for the insufflation of hot air was applied at the borders of the burner to represent the flame that is the heat source for the oven. As a uniform inlet, an exaggerated flow speed of $2.5m/s$ and a temperature of $1200K$ were adopted for the sides of the burner to accelerate the thermal behavior of the model for analysis purposes.

3.4 Numerical Solver

To solve the model presented in this work, the open-source OpenFOAM v1921 CFD software was used. The multi-region solver that contemplates the conduction, radiation, and transient convection processes for solids and fluids, chtMultiRegionFoam was used. Considering the effects of energy dissipation and fluid instability in motion, the $k - \epsilon$ turbulence model was used. In this work, heat exchange through radiation was not considered.

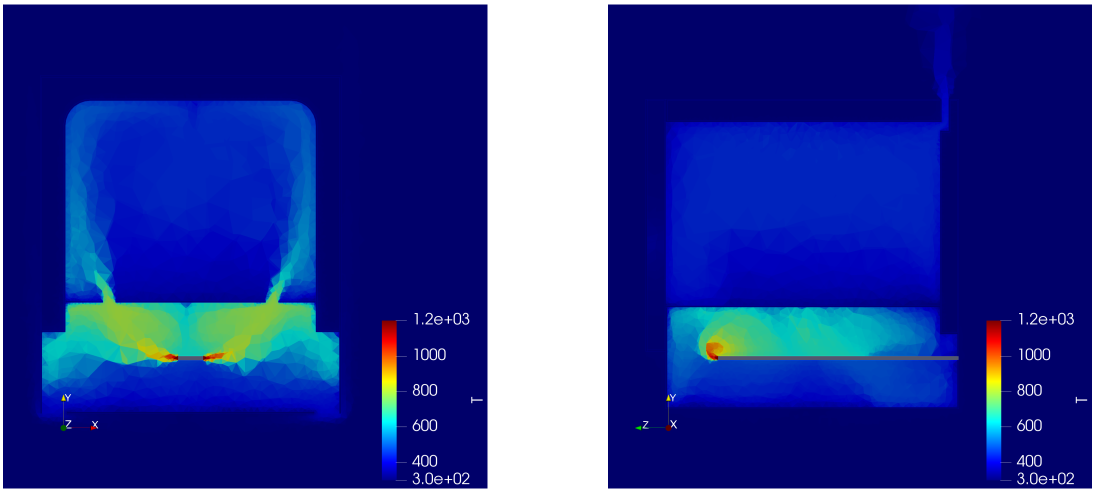
4 Results

The results obtained shown below are from the last time step recorded during the solution process, representing a running time of 53 seconds from the initial condition. The process has not yet reached equilibrium and, therefore, the result should be considered as partial.

4.1 Temperature

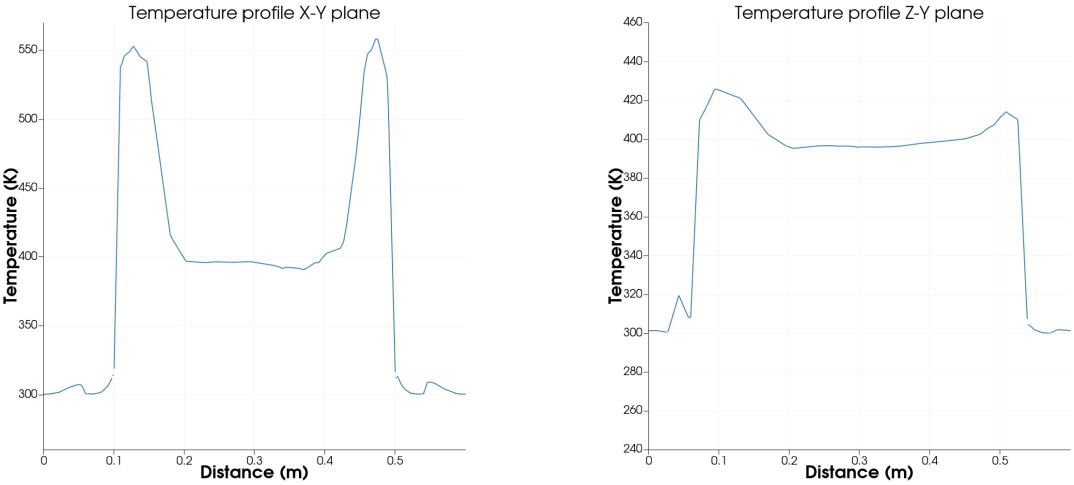
The Fig. 4 brings the temperature fields in cuts in half the domain along the width and depth of the oven. In this partial result, a large temperature difference is observed between the cavity where the burner is located and the cavity where the food is cooked. It is also possible to notice the tendency of the flow to be directed towards the side walls, probably due to the holes in the false bottom.

The graphs shown in Fig. 5 bring the temperature profiles over a line at $0.45m$ from the floor, just above the false bottom, on the same planes as Fig. 4, starting at $0.025m$ from the left wall (Fig. 5a) and the same distance shown in Fig. 5b, starting from the front of the door. The higher temperature in the side of the cooking cavity is evident, as well as the insulating effect of the glass wool blanket on the sides and at the top. The confined air in the door has an unexpected temperature rise.



(a) Frontal plane (b) Lateral plane

Figure 4. Temperature field cuts



(a) Frontal plane (b) Lateral plane

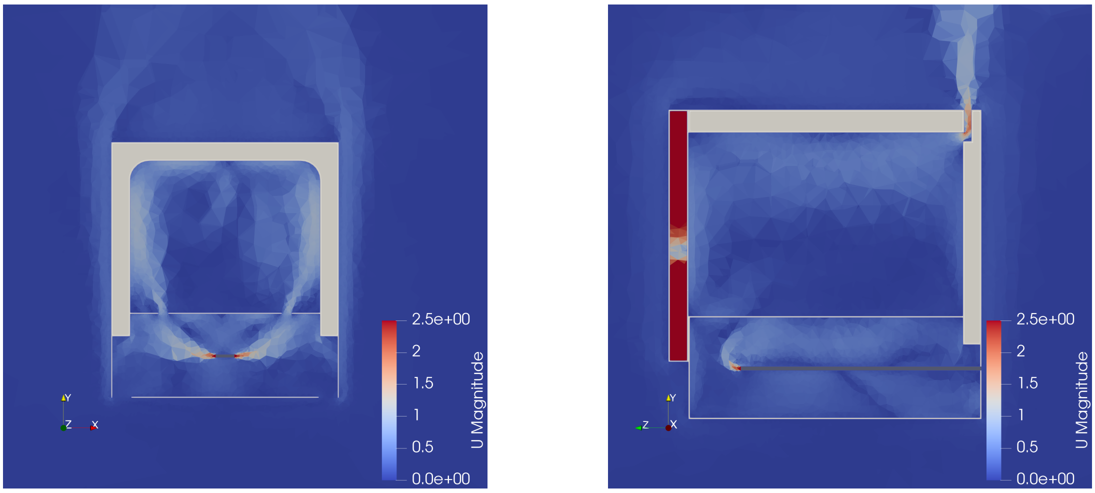
Figure 5. Temperature profile over line

4.2 Velocity

In the same positions as the temperature cuts, Fig. 4 brings the velocity fields obtained in the solution. It is possible to perceive in the Fig. 4a the overflow effect of the warmer air inside the internal fluid cavity, thus making it exit both through the outlet at the rear (Fig. 4b) and in the cold air inlets from below and, consequently, climbing up the sides. Also in Fig. 4b, it is possible to notice an abnormal velocity increase in most of the confined air volume of the front door. Due to this error, the results obtained for this specific region should be disregarded.

5 Conclusions

The results obtained in this work, although initial, provide an orientation panorama about the trend of heat loss in the domestic oven and, consequently, the regions with the highest risk of accidents. The sides of the internal cooking cavity are bathed at all times by the warmer air coming out of the burner cavity, leading to the need for study with longer operating time. It is also an object of interest the walls of the burner cavity, which do not have insulating material separating the hot air from the metal sheet and then the environment, being able to warm up at a much higher rate over time. For future work, the problem in the confined air region of the front door is expected to be corrected, ensuring the correct thermal behavior of this region that is of most interest. The solution for a longer operating time is also necessary, as is the evaluation of the result with the supply of hot air closer to the normal operating parameters of the domestic oven.



(a) Frontal plane (b) Lateral plane

Figure 6. Velocity field cuts

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