Integration of Finite Element Analysis Results into Multi-domain Modeling for Food Production Plant Simulation

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Abstract: In recent years, the use of simulation in industrial processes and research has grown significantly, largely due to computational technology advancements. Techniques like Computational Fluid Dynamics (CFD), Finite Element Methods (FEM), simulations are widely used across various fields. In the food industry, multidomain simulation codes have optimized cooking and cooling times in critical equipment such as ovens and kettles. However, highly detailed simulations, especially for heat transfer in cooking processes, require substantial computational resources, often surpassing the capabilities of multidomain approaches. This work focuses on simulating an oven and kettle used in ham production. The cooking process is modeled using COMSOL Multiphysics to determine optimal cooking times and temperatures. The resulting temperature and time data are exported to Wolfram SystemModeler to control steam of the on/off cycles of the heaters precisely.Results show a strong correlation between COMSOL and Wolfram simulations, with a 5 % error in cooking time for the kettle and a 15 % deviation in steam generation. Similarly, the oven presents a 5 % error between simulated and experimental cooking values. The integration of FEM-based simulations with multidomain modeling enhances the accuracy of heating time predictions, contributing to the optimization of food production processes.

Palabras clave: Heat transfer simulation, Finite Element Method (FEM), Multi-domain modeling, Computational fluid dynamics (CFD), Control system modeling, Real-time process control

Integración del Análisis por Elementos Finitos en la Modelización Multidominio para Plantas de Alimentos

Resumen: En los últimos años, el uso de simulaciones en procesos industriales e investigación ha crecido significativamente gracias a los avances en tecnología computacional. Técnicas como la Dinámica de Fluidos Computacional (CFD), los Métodos de Elementos Finitos (FEM) se aplican ampliamente en diversos campos. En la industria alimentaria, los códigos de simulación multidominio han optimizado los tiempos de cocción y enfriamiento en equipos como hornos y marmitas. Sin embargo, las simulaciones detalladas, especialmente en transferencia de calor, requieren importantes recursos computacionales que a menudo superan las capacidades de estos enfoques. Este trabajo simula un horno y una marmita empleados en la producción de jamón, modelando el proceso de cocción en COMSOL Multiphysics para determinar tiempos y temperaturas óptimas. Los datos se exportan a Wolfram SystemModeler para controlar con precisión los ciclos de calentamiento, mostrando una alta concordancia entre ambas plataformas. Los resultados muestran una alta correlación entre las simulaciones de COMSOL y Wolfram, con un error del 5 % en el tiempo de cocción de la marmita y una desviación del 15 % en la generación de vapor. De manera similar, el horno presenta un error del 5 % entre los valores de cocción simulados y experimentales. La integración de simulaciones basadas en FEM con modelado multidominio, mejora la precisión en la predicción de tiempos de calentamiento, contribuyendo a la optimización de los procesos de producción de alimentos.

Keywords: Simulación de transferencia de calor, método de los elementos finitos (MEF), modelización multidominio, dinámica de fluidos computacional (CFD), modelización de sistemas de control, control de procesos en tiempo real

1. INTRODUCTION

The industry of food production is constantly evolving and is a topic of vital importance to ensure the food supply. It is estimated, for example, that between 25 % and 60 % of food is wasted before it reaches the consumers (Kasso & Bekele, 2018; Shoji et al., 2022). This trend varies by country, but in general, it is closely related to inefficient use, waste, and poor management of energy

and water resources, which leads to economic losses (Virginia et al., 2017).

This problem is exacerbated in less industrialized countries, where food production plants face even greater challenges due to poor traceability and low automation of their production lines, resulting in lower energy efficiency, unsustainable processes, and low-quality products (Fróna et al., 2019).

In this context, the design and optimization of food production plants have become increasingly complex, requiring the use of technologies that integrate different physical domains, such as thermal dynamics and fluid mechanics (Fadiji et al., 2018; Fadiji et al., 2021). An emerging trend that promises to improve production performance, efficiency, and quality without requiring additional infrastructure is the digitalization of production processes. This concept, known as digital twins, is essential for improving processes in any industry (Udugama et al., 2021; Udugama et al., 2023).

Several software programs have been developed with the intention of simulating the management of production plants, but many of them have limitations (Sumit et al., 2021). For example, in the simulation of food production lines, heuristic methods are used to analyze heating and cooking, while others only simulate the response time of actuators to input signals such as temperature and pressure (Howard et al., 2023; Morgan & Haley, 2013). While these tools help optimize the management of energy resources, they lack a deeper analysis of the physical effects involved during food heating and cooking.

Another alternative is the use of the finite element method (FEM), widely recognized as a powerful tool that provides a detailed view of thermal effects, which are critical for ensuring the reliability and safety of food production processes. Although FEM addresses the mechanical and thermal effects of food cooking in detail, its use has traditionally been limited to isolated domain analysis, which can be a significant drawback in the context of complex systems such as food production plants, which operate at the intersection of various physical phenomena (Fadiji et al., 2018; Fadiji et al., 2021). The challenge lies in integrating FEM results into multidomain modeling platforms that can simulate these interactions comprehensively, providing a more accurate representation of real-world food production conditions in plants (Mourtzis et al., 2014).

A powerful alternative to improve the accuracy of simulations is to couple finite element analysis (FEM) codes with multidomain simulations, either through external/internal coupling or OLE for Process Control OPC (Li & Nakagawa, 2002). This integration enables high-fidelity results by leveraging the strengths of both approaches: FEM for detailed analysis of physical phenomena and multidomain simulations to study the interactions between different subsystems. Although this methodology is well-developed in other fields of engineering, such as automotive, aerospace, and nuclear (Almachi et al., 2024; Bonazzoli & Claeys, 2024), its application in the simulation of food production plants remains largely unexplored. Some studies have attempted to integrate finite element analysis into food processing simulations e.g., (Fadiji et al., 2018; Howard et al., 2023), but comprehensive multidomain modeling approaches remain limited.

In this work, only main components of a food industry are simulated, accordingly plant consisting of a jacketed kettle, an oven, and steam distribution valves. First, the heating and cooking times and temperatures of the marmite inside the jacketed kettle and oven are obtained using the FEM tool in COMSOL Multiphysics (Choi et al., 2015). These data are then integrated into a multidomain physical modeling program, Wolfram System Modeler, (Otter, 2021), to simulate the behavior and response time of the mass flow rate of steam supplied to the jacketed kettle and the opening of the steam distribution valve. This proposed methodology facilitates a better understanding of the interactions within production plants, offering a holistic approach to the challenges facing the food production industry. This research contributes to the growing big data, a fundamental element for the development of digital twins applied in food production (Tzachor et al., 2022).

This work is structured as follows: first, a brief description of the different methodologies used for the simulation of food production plants is provided, highlighting their importance, along with a general description of the plant under analysis. Then, the proposed methodology is presented, including an explanation of the software tools used and the key elements simulated, where the temperature and time data obtained from COMSOL simulations are extracted and subsequently integrated into the Wolfram System Modeler for further analysis. Next, the results are analyzed for the oven and kettles, showing the temperature evolution over time for these units, as well as the evaluation of the opening and closing curves of the steam mass flow supplied to the steam oven during the cooking cycle and the performance of the steam distribution valve. Additionally, a comparison between the simulation results and experimental data is presented. Finally, the main conclusions and perspectives of this study are summarized, highlighting key findings and potential future improvements.

2. BRIEF DESCRIPTION OF THE PRODUCTION PLANT

The plant that is being used as a reference for creating the model was taken from the energy audit work by (Palacios, 2009). This plant carries out various processes with meat products, one of which is the production of sausages (Palacios, 2009). This plant has a steam system responsible for generating, distributing, and utilizing the energy contained in the steam for cooking food (Palacios, 2009).

For the steam generation process, this plant has a four-pass fire-tube boiler with its respective fuel and water supply systems (Palacios, 2009). In the distribution system, there is an arrangement of pipes and valves responsible for directing steam to the consuming equipment and controlling its flow as needed. This process is carried out automatically, thanks to a temperature control system located in the consuming equipment, which sends a signal to open the valves, allowing steam to pass through when the temperature of the working fluid (water for kettles and air for ovens) falls below a set limit. Similarly, a signal is sent to close the valves when the temperature of the working exceeds the established limit. These limits will depend on the process being carried out (Palacios, 2009).

Finally, among the steam-consuming equipment in the plant includes kettles and ovens, where the operating conditions will depend on the type of process intended for the various meat

products (Palacios, 2009). In this work, the behavior of a boiler representing the steam generator, a valve representing the steam distributor, and a kettle and an oven representing the consuming equipment will be analyzed.

3. METHODOLOGY

In order to understand the thermodynamic and heat transfer analysis in industrial cooking systems, simulation models of the consuming equipment have been developed for a food plant, specifically focused on the simulation of a jacketed kettle and a steam oven. Figure 1 shows a diagram of the methodology to be followed during the development of the article.
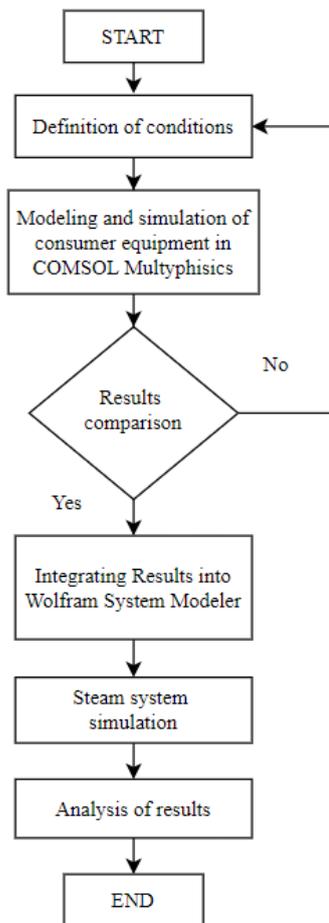

Figure 1. Diagram of the methodology

3.1 COMSOL Multiphysics

COMSOL Multiphysics is a program designed for modeling and simulation through finite element analysis (FEM), where it is possible to solve multi-domain problems, define characteristics, dimensions, materials, boundary conditions, among others (Almachi & Montenegro, 2016; Wei, 2010). This program has a user-friendly interface that allows to perform a wide range of physical phenomena (Vajdi et al., 2020).

Once all the model parameters have been defined, the program discretizes the domains and solves the equations by means of finite element analysis (FEM). Finally, it allows visualization and

analysis of the data obtained by means of graphs, tables and other post-processing tools available in the program (Vajdi et al., 2020).

COMSOL Multiphysics can be used to model the prediction of temperatures in cooking, pasteurization, drying and other processes (Salvi et al., 2011). In addition, it allows modeling heat and mass transfer during the different processes (Wei, 2010). This makes it possible to integrate physical phenomena in a single model and thus develop more complex processes.

Two independent models are developed, one for the jacketed kettle and another for the steam oven, to analyze the thermal behavior and the cooking process of the food inside them. To perform the simulation, the thermophysical properties of the materials, including: density, thermal conductivity, thermal diffusivity, and specific heat were considered. These values were obtained from the literature and are detailed in Çengel & Boles (2019).

Figure 2 (a) shows the typical physical form of a jacketed kettle, which is composed of the elements of cooking chamber, hermetic cover, leveling base and controls. In order to simulate the jacketed kettle, the following points described below are considered.
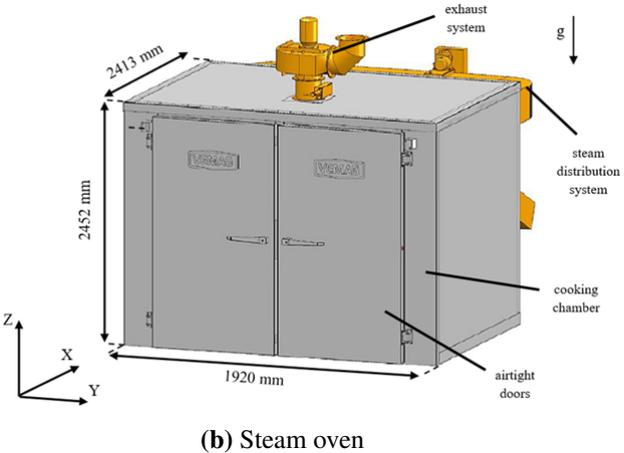

(a) Jacketed kettle

(b) Steam oven

Figure 2. Representations of (a) the jacketed kettle and (b) the steam oven, with main parts labeled. Images modified from (Equipo-H, 2024) and (Quiroz & Villacís, 2020).

For the simulation of the jacketed kettle, dimensions and physical characteristics are defined. Table 1 shows equipment dimensions, coil dimensions and materials.

Table 1. Dimensions of the main elements of the jacketed kettle and the steam oven obtained from (Equipo-H, 2024) and (VEMAG, 2007).

Specifications	Jacketed Kettle	Steam Oven
Capacity (m³)	0.5	11.4
Dimensions (mm)	$1\,060.0 \times 600.0$	$1\,920.0 \times 2\,452.0 \times 2\,413.0$
Coil length (m)	12.4	5.0
Coil diameter (mm)	34.0	50.8

The amount of feed to be included is obtained using a mass ratio of 2:1 between the fluid and the feed (Palacios, 2009), so that a total mass of ham equivalent to 172 kg is defined. According to data from a sausage manufacturer, an approximate diameter of 134 mm is defined for each piece, so that an approximate of 14 pieces are included in each cycle.

Jacketed Kettle model considerations

The symmetrical of the model allows for a simplified 2D representation, which streamlines equations and calculations while minimizing computational resource usage. It is assumed that the temperature of the outer wall of the coil pipe matches that of the steam flowing through it, with the steam temperature remaining constant. No insulation exists between the vat and kettle casing, leading to convection with the environment, characterized by a coefficient of 10.7 W/m² - °C (Palacios, 2009). Ham pieces are evenly distributed across the control surface, and within the kettle, fluid movement occurs due to temperature gradients caused by natural convection. Simulation timing varies based on when target temperatures are achieved, optimizing calculation efficiency.

Steam oven

Figure 2 (b) shows the typical physical form of an oven. In order to simulate it, the following points described below are taken into account.

For the steam oven simulation, dimensions and physical characteristics are defined. Table 1 shows equipment dimensions, coil dimensions and materials.

The amount of feed to be included is obtained using a mass ratio of 4:1 between the fluid and the feed (Palacios, 2009), therefore, just as in the jacketed kettle, a total equivalent mass of ham is defined, which, according to the food manufacturer's dimensions, is approximately 66 pieces of ham per cycle.

Steam oven model considerations

The model is assumed to be symmetrical, allowing for a sufficient 2D representation that simplifies the necessary equations and calculations, thereby reducing computational resource requirements. It is further assumed that the temperature of the outer wall of the coil pipe matches that of the steam passing through it, with the steam temperature considered constant. No insulation elements are included between the interior walls and the oven shell, leading to convection with the environment characterized by a coefficient of 10.7 W/m² - °C (Palacios, 2009). Ham pieces are uniformly distributed across the control surface,

and within the oven, fluid movement occurs due to temperature differences from heat transfer by natural convection. The timing of the simulations is variable, depending on when the target temperatures are reached, allowing the simulation to stop at that point for efficient calculations.

Results

The temperature measurements in the jacketed kettle were taken at three evenly distributed points on the surface, as illustrated in Figure 3 (a). These reference points, marked in red, have the following coordinates (in mm): (0, 0) (center of the geometry), (0, 400) (upper section), and (0, -400) (lower section).

In addition, several points on the food sample, marked in blue, were selected for temperature monitoring. These points are located at (-150, 0) (center of the food), (-150, 450) (upper section of the food), and (-150, -450) (lower section of the food). These measurements ensure that the temperature distribution within the food is accurately assessed.
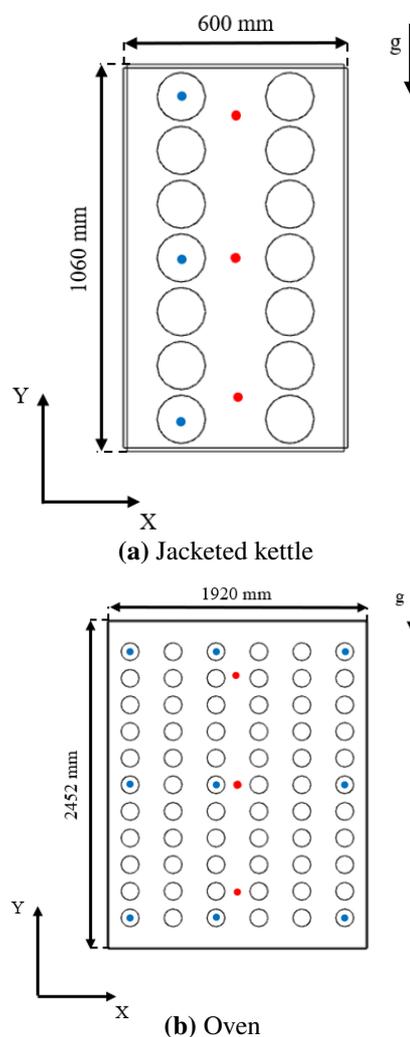

(a) Jacketed kettle

(b) Oven

Figure 3. Axial distribution of logger points for obtaining temperature values: (a) inside the jacketed kettle, and (b) inside the oven. Red indicates the fluid, and blue indicates the ham. Images modified from original sources.

For the steam oven, the temperature measurement process follows

the same methodology as in the jacketed kettle, but with different reference points, as shown in Figure 3(b). The fluid temperature is recorded at three red-marked points with coordinates (in mm): (0, 0) (center of the geometry), (0, 800) (upper section), and (0, -800) (lower section). Additionally, several measurement points were selected on the food sample to monitor its internal temperature. These points, marked in blue, have the following coordinates: (-800, 1005) (top-left), (-800, 0) (middle-left), (-800, -1005) (bottom-left), (-160, 1005) (top-center), (-160, 0) (center), (-160, -1005) (bottom-center), (800, 1005) (top-right), (800, 0) (middle-right), and (800, -1005) (bottom-right). Finally, Table 2 presents the simulated temperature and time values obtained with COMSOL, which will be integrated into the Wolfram code.

Table 2. Fluid and ham temperature as a function of time for the jacketed kettle (JK) and steam oven (SO)

Equipment	Action	Time (s)	Fluid Temp (°C)	Ham Temp (°C)
JK	Water heating	7 815	87.80	11.80
JK	Decrease 1	2 273	83.60	30.06
JK	Increase 1	1 880	86.09	42.77
JK	Decrease 2	2 311	83.60	65.77
JK	Increase 2	2 049	87.80	74.74
SO	Air heating	3 034	86.00	11.80
SO	Decrease 1	369	80.00	20.32
SO	Increase 1	1 185	86.00	29.69
SO	Decrease 2	1 367	80.00	37.75
SO	Increase 2	1 033	86.00	46.52
SO	Decrease 3	3 539	80.00	57.24
SO	Increase 3	865	86.00	66.79
SO	Decrease 4	2 528	82.62	74.28

3.2 Integration results to Wolfram system modeler

Wolfram System Modeler is a tool designed for computational modeling and simulation of complex multi-domain physical systems, working with the Modelica language. This software features a user-friendly interface that allows users to create system models using components loaded from an extensive library through a drag-and-drop method (Augello, 2021).

Modelica is an object-oriented language that, unlike other object-oriented programming languages like C++ or Java, handles systems of equations symbolically, determines their execution order, and indicates which components of the equation will represent inputs or outputs. This makes it ideal for multi-domain system modeling, as it enables high-performance numerical work while allowing users to focus on describing the behavior of components rather than solving complex equations or performing data post-processing (Augello, 2021).

Based on the above, Wolfram System Modeler is a tool capable of modeling and simulating the behavior of complex and multi-domain systems, such as in this case, a food production plant operating with steam systems.

To model the steam system in Wolfram System Modeler, it is necessary to first know the components and how they function. Generally, a steam system consists of a steam generation section, a steam distribution section, and a steam consumption section.

In the system modeled in this work, the steam generation section will be represented by a boiler, which will have a control system

coupled to it for the feedwater intake. The steam distribution section will be represented by a valve responsible for allowing the steam to pass to the consumption equipment. The steam consumption section will be represented by a jacketed kettle in the first example and by a steam oven in the second example.

Temperature and time data obtained from COMSOL Multiphysics were integrated into Wolfram System Modeler to simulate the dynamic behavior of the steam heating system. However, during the integration process, discrepancies between the different data sets were identified, mainly due to differences in spatial resolution, numerical interpolation methods, and transient response characteristics between the two platforms. To minimize these discrepancies, a data smoothing and interpolation procedure of the temperature profiles over time was applied. These corrections improved the agreement between the COMSOL simulated temperatures and the dynamic response of the Wolfram Modeler, resulting in a more accurate representation of the operating behavior of the heating system.

Steam generation

The boiler modeled in this section will be governed by the conditions indicated in Table 3.

Table 3. Operating and initial conditions for the boiler, jacketed kettle, and steam oven (Palacios, 2009)

Equipment	Condition	Value
Boiler	Capacity (m³)	9.28
Boiler	Operating temperature (°C)	168.50
Boiler	Operating pressure (kPa)	764.28
Jacketed Kettle	Capacity (m³)	1.50
Jacketed Kettle	Initial temperature (°C)	16.00
Jacketed Kettle	Initial pressure (bar)	1.00
Steam Oven	Capacity (m³)	11.36
Steam Oven	Initial temperature (°C)	20.00
Steam Oven	Initial pressure (bar)	1.00

Within the boiler, the water level must remain constant at a value of 6.5 m³, so a control system will be implemented to regulate the operation of the feedwater pump, ensuring that the flow rate from the pump is sufficient to maintain the water level in the boiler as required.

In the steam generation section model, there will be a boiler, a feedwater pump, a proportional-integral (PI) control system for water injection, and a burner. PI control system for water injection and a burner control system for water injection, and a burner. The behavior of the burner will be governed by an activation signal defined through a table of values, which specifies the amount of heat the burner must supply over time.

The heat values will vary between 0 and 2 MW when the consumption equipment is in the cooling and heating cycles, respectively. The time values for these cycles are obtained from the simulation carried out in COMSOL Multiphysics. Table 4 shows the values that will govern the behavior of the burner when the jacketed kettle is used as a steam consumption equipment.

Considering that the cooking processes in both the jacketed kettle and the steam oven are different, there will be different time values in the table that govern the behavior of the burner when a steam

Table 4. Energy emitted by the burner, valve opening and food temperature with the jacketed kettle as the consumer

Simulation time (s)	Energy emitted (MW)	Valve opening	Food temperature (K)
0	2	1	284.95
7 815	2	1	284.95
7 816	0	0	284.95
10 089	0	0	303.21
10 090	2	1	303.21
11 970	2	1	315.92
11 971	0	0	315.92
14 282	0	0	338.92
14 283	2	1	338.92
16 332	2	1	346.88

oven is used as the consumption equipment.

Steam distribution

The valve that allows steam to pass to the steam consumption section will be activated and deactivated by a signal, which will also be defined by a table of values. A value of 1 will indicate a full opening of the valve, while 0 will indicate that it is closed. Similarly, the times at which the valve will open are the same as those defining the cooling and heating cycles described previously. Table 4 presents the parameter values that define define the operation of the valve when the steam consumer is a jacketed kettle.

Steam consumption

In the case where the steam consumer is a jacketed kettle, the initial conditions will be as detailed in Table 3. The jacketed kettle will be represented by a closed volume containing water inside, which is heated through heat transfer between the water and a coil carrying steam from the distribution section. To represent the cooking of the food, a heat transfer function by convection will be added between the hot water and an external body (representing the food), that will have a variable temperature. The temperature is obtained in COMSOL Multiphysics through the process described in the previous section, for each time interval. These values will also be entered into the model via value tables to indicate the food temperature at the end of each of the cycles. Table 4 shows the food temperature values at the end of each cycle when the jacketed kettle is the steam consumer.

On the other hand, when the steam consumer is the oven, the initial conditions will be as detailed in Table 3.

4. RESULTS AND DISCUSSIONS

4.1 Thermal simulation results: COMSOL vs Wolfram System Modeler

Figure 4 (a) presents the temperature evolution inside the kettle over time as obtained from both COMSOL Multiphysics and Wolfram System Modeler simulations. Initially, the temperature rises from room temperature to 87.8 °C during the preheating stage, then decreases to 83.6 °C in the cooling phase, before increasing again to 87.6 °C. This cycle of heating and cooling repeats, maintaining the internal temperature within this range until 16 328 s, when cooking is completed. The heat transfer

occurs through convection, where steam transmits thermal energy to both the fluid and the food inside the kettle. As a result, a temperature gradient is established during each cycle, increasing when steam flow is active and decreasing when steam supply is interrupted. The comparison between COMSOL Multiphysics and Wolfram System Modeler curves reveals a strong overall agreement, with minor deviations, particularly during the cooling phases. Additionally, an atypical behavior is observed during the initial seconds of the preheating stage, where the temperature response differs between the two models before gradually converging. These discrepancies may be attributed to differences in numerical solvers, initial boundary conditions, or the integration of results between both platforms.

Figure 4 (b) shows a graph of temperature vs. time inside the oven as obtained from both COMSOL Multiphysics and Wolfram System Modeler simulations, where it can be seen that the temperature increases from room temperature to 86 °C during the preheating stage, then decreases to 80 °C during the cooling stage, followed by heating up to 86 °C, and the heating and cooling cycles are repeated, maintaining the interior temperature in a range between the values mentioned above until a time of 13 920 s when cooking is completed. The heat provided by the steam is transmitted by convection to the fluid and the food inside, obtaining a temperature gradient during the stages of the cycle, which increases when there is a flow of steam and decreases as soon as its passage through the coil is interrupted. Finally, in general, the curves show a good approximation according to the graph provided, with slight deviations, especially during the cooling stages. However, in the preheating interval, an atypical behavior is observed during the initial seconds until both curves align. Additionally, in the last cooling cycle, a significant difference is observed between both graphs, which could be due to the initial considerations defined during the integration of results. Since this study is focused on a specific industrial context, direct comparisons with other studies are not feasible due to differences in process conditions, equipment, and operational parameters. Nevertheless, our findings establish a baseline for future research in food production process simulation, providing a methodological framework that could be adapted to other similar industrial settings. Further experimental validation in different environments would help assess the broader applicability of the proposed approach.

### 4.2 Dynamic behavior of steam flow and control system

Figure 4 (c) shows a graph of steam flow vs. time in the jacketed kettle, where the steam flow increases up to 0.54 kg/s during the preheating stage, then decreases to a value close to 0 kg/s during the cooling stage and then increases again during the heating stage up to 0.57 kg/s. This behavior is repeated until the end of the cooking cycle, as well as the temperature. The steam flow varies according to the heat transfer to the fluid and the food inside the jacketed kettle, where it keeps increasing until a desired internal temperature is reached and then it is mostly interrupted until the temperature decreases in a certain range. In addition, this behavior is associated with Figure 4 (d), which shows the valve opening vs. time, in which a sensor measures the internal temperature of the equipment and transmits the signals to the controller, so
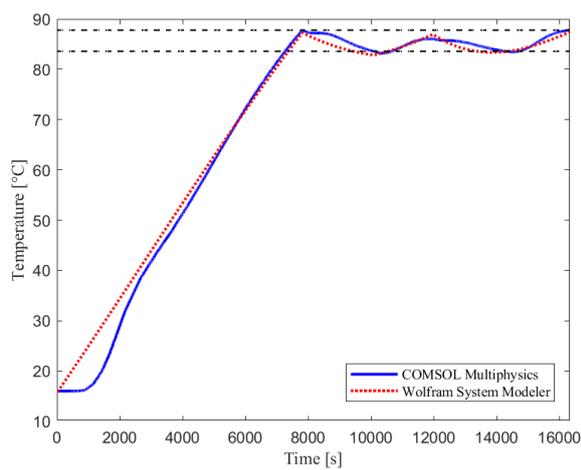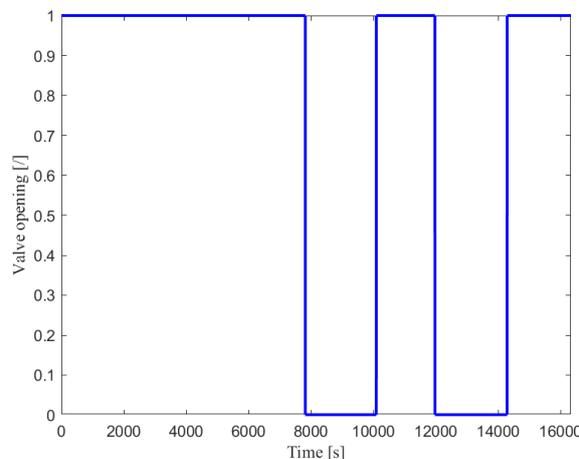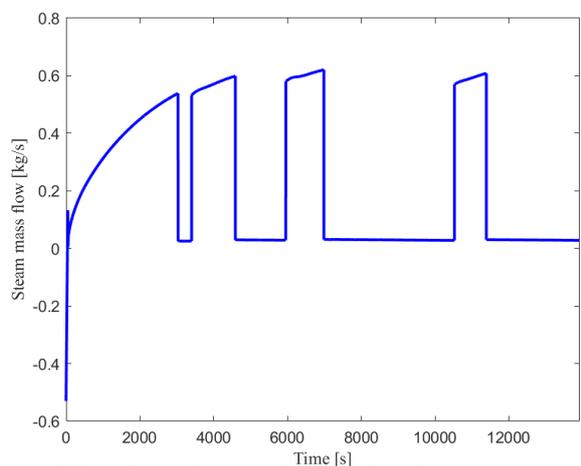
(a) Jacketed kettle
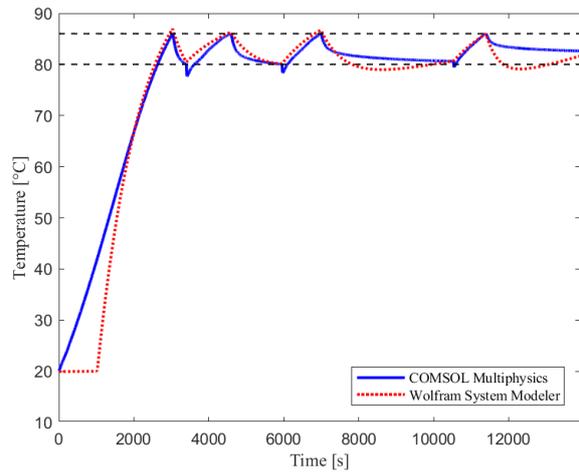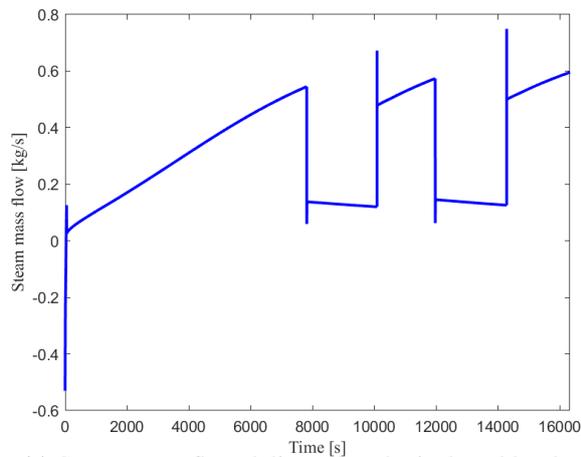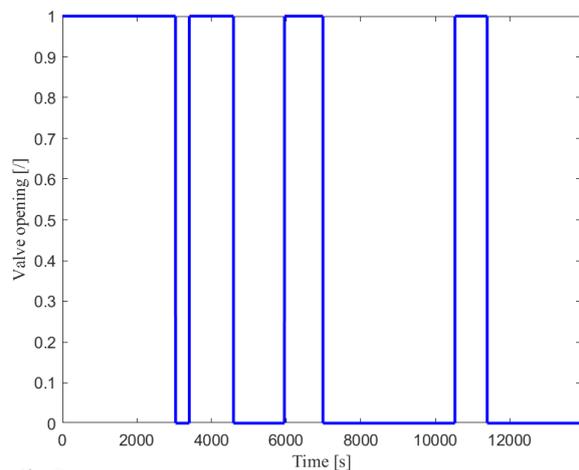
(b) Steam oven

(c) Steam mass flow delivered to the jacketed kettle during the cooking cycle, no experimental results for comparison

(d) Opening of the distribution valve during the cycle in the jacketed kettle

(e) Mass flow of steam delivered to the steam oven during the cooking cycle, no experimental results for comparison

(f) Opening of the distribution valve during the cycle in the steam oven

Figure 4. Comparison of steam mass flow and valve opening during cooking cycles, and fluid temperature comparisons: (a) Jacketed kettle: Comparison of fluid temperature in the kettle. (b) Oven: Comparison of fluid temperature in the oven. (c) Steam mass flow in the jacketed kettle. (d) Valve opening in the jacketed kettle. (e) Steam mass flow in the steam oven. (f) Valve opening in the steam oven.

that depending on these signals the valve opening is increased or reduced, reaching the desired temperatures. In general, the graphs are good because they show the correct operation of the control system according to the temperatures reached.

Figure 4 (e) shows a graph of steam flow vs. time in the kettle, where it is identified that the steam flow increases up to 0.53 kg/s during the preheating stage, then decreases to a value close to 0 kg/s during the cooling stage, and then, there is a new increase during the heating stage up to 0.59 kg/s, similar to the temperature, this pattern is repeated until the cooking cycle ends. The steam flow varies according to the heat transfer to the fluid and the food in the kettle, increasing progressively until the desired internal temperature is reached. Then, the steam flow is significantly reduced until the temperature drops within a specific range. This behavior is related to Figure 4 (f), which shows the valve opening over time. A sensor measures the internal temperature of the equipment and sends signals to the controller, which adjusts the valve opening as necessary to achieve the desired temperatures. In general, the graphs are satisfactory as they demonstrate the correct operation of the control system in relation to the temperatures reached.

4.3 Comparison between simulated and experimental results

Using the available data from reference documents on the actual behavior of the steam-consuming equipment, along with the results obtained from simulations in Wolfram System Modeler, a comparison was conducted to evaluate the level of error. For the jacketed kettle acting as a steam consumer, Table 5 presents a comparison between the actual and simulated data for both cooking time and steam flow, along with the corresponding error percentage. Similarly, for the steam oven, Table 5 compares the actual and simulated cooking times, including the generated error. Based on the data presented in Table 5, a strong agreement is observed between the actual and simulated values, with a maximum recorded error of 15 %.

Table 5. Operating conditions of the boiler obtained from (Palacios, 2009)

Parameter	Experimental data	Simulated data	Error (%)
Jacketed Kettle			
Cooking time (h)	2.40	2.28	5.00
Steam flow (kg/s)	0.55	0.65	15.00
Steam Oven			
Cooking time (h)	2.86	3.00	5.00

5. CONCLUSIONS AND OUTLOOK

In this study, the thermal behavior of a jacketed kettle and a steam oven was analyzed through computational simulations using COMSOL Multiphysics and Wolfram System Modeler. A comparative analysis between simulated and experimental data showed good agreement, with a maximum error of 15 % in steam flow predictions and 5 % in firing time estimates. These results validate the proposed simulation methodology for

predicting heat transfer dynamics in steam cooking equipment while also highlighting areas where improvements can be made, particularly in transient cooling phases where deviations were more pronounced.

The main contribution of this work lies in the integration of FEM-based simulations (COMSOL) with system-level modeling (Wolfram System Modeler), providing a detailed, multi-domain approach to understanding heat transfer in food processing. Unlike previous studies, which primarily rely on experimental data or simplified empirical models, this methodology enables a more physics-driven and computationally precise optimization of process parameters and real-time control strategies for heaters and steam mass flow regulation.

Although direct comparisons with previous studies are limited due to differences in methodologies and equipment configurations, the findings presented here establish a computational framework that can serve as a reference for future research in food industry simulation. The results indicate that coupling FEM simulations with system-level modeling enhances process efficiency and energy optimization, making it a viable tool for improving industrial food production.

Future work will focus on refining the simulation by incorporating adaptive control strategies and real-time data acquisition, further improving the predictive capability of the model and its applicability in various industrial environments. Additionally, further validation with expanded experimental datasets would help assess the broader applicability of this approach to different cooking systems and operational conditions.

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