

# Transient 2D Simulation of Heat Transfer in Food Trays through Conduction and Convection

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## Abstract

*This study presents a numerical simulation of heat distribution and cooling behavior in food placed within a food tray. The heat transfer model incorporates both conduction and convection mechanisms, solved numerically using finite difference method. The tray is represented as a rectangular domain measuring 20×15 cm, with three localized heat sources that mimic the initial temperature distribution of cooked food. Convective cooling from ambient air is applied uniformly along all tray boundaries. The simulation results demonstrate the spatial and temporal evolution of temperature, showing that heat propagates from the food regions toward the tray walls, causing a short-term rise in the average temperature before gradually decreasing due to conduction–convection interactions. This numerical model successfully visualizes how temperature dissipates over time and highlights the influence of boundary conditions on the cooling rate. The findings offer a useful reference for understanding heat transfer phenomena in packaged food systems and can support the optimization of food tray design and cooling strategies to maintain food safety and quality.*

**Keywords:** Heat Distribution Simulation, Food Tray, Conduction, Convection

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## 1. INTRODUCTION

Heat transfer plays a fundamental role in food technology, particularly in the cooling phase that follows cooking. This process not only determines the sensory quality and texture of food but also has critical implications for microbiological safety. Prolonged exposure to certain temperature ranges can accelerate the growth of pathogenic microorganisms. Uneven temperature distribution for instance, when the edges of a meal cool faster than its center can lead to inconsistent doneness or even create “danger zones,” where microbial proliferation occurs rapidly. Therefore, a clear understanding of heat distribution dynamics within food and its container is essential to ensure both product quality and safety.

Many studies have examined how heat transfer occurs in food materials and processing systems, focusing on how conduction and convection work together to shape temperature distribution and cooling performance. For example, investigated the effects of conduction and convection on temperature distribution and drying rates in biomass materials (Nabila et al., 2023). Examined how air temperature and flow rate influence the drying characteristics of food products (Prasetyaningsih & Billah, 2018), and conducted a basic simulation of conductive heat distribution in metals (Nurullaeli & Mahisha Nugraha, 2021). These studies highlight the importance of numerical and experimental approaches in analyzing thermal phenomena, though most focus on drying or heating rather than post-cooking cooling behavior.

Food safety has become a major public concern in Indonesia following several mass poisoning incidents linked to the *Makan Bergizi Gratis* (MBG) program. Since its rollout, numerous cases have been attributed to failures in meeting food safety standards and proper handling procedures. Media reports note that more than 6,500 students experienced digestive illness between January and September 2025 after consuming MBG meals (Jakarta Globe, 2025). Similar symptoms: nausea, vomiting, and dizziness were reported in Cianjur, Garut, and Banggai Kepulauan, suggesting that temperature control and sanitation during storage and distribution were insufficient (Kompas, 2025).

In such situations, heat transfer within food and its container primarily occurs through conduction and convection, the two mechanisms most relevant to understanding how temperature changes during post-cooking storage.

Conduction refers to the transfer of thermal energy through a solid material without any bulk movement of the material itself. Heat flows as faster-moving, higher-energy particles transfer their energy to neighboring particles with lower kinetic energy. This phenomenon is described by Fourier's law, which relates the heat transfer rate to the temperature gradient and the material's thermal conductivity ( $k$ ). In two-dimensional (2D) time-dependent heat transfer simulation, the transient heat-conduction equation can be written as:

$$\rho c_p \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (1)$$

where  $\rho$  is density,  $c_p$  is specific heat capacity, and  $T(x, y, t)$  represents the temperature field over space and time. This equation can capture the diffusion of heat within a material caused by local temperature differences (Cordioli et al., 2016).

Convection is the heat-transfer process driven by the motion of a fluid like air, the air surrounding the food tray. During cooling, heat leaves the tray surface and is carried away by the air, a process expressed by:

$$Q = h(T_s - T_\infty) \quad (2)$$

where  $Q$  is the heat flux (the rate of heat transfer per unit area,  $\text{W}/\text{m}^2$ ),  $h$  is the convective heat-transfer coefficient,  $T_s$  the tray surface temperature, and  $T_\infty$  the ambient air temperature. In this system, heat moves outward by conduction within the food and then dissipates to the air through convection (Chen et al., 2020).



**Figure 1.** Illustration of the food tray shape

In food engineering, thermal simulations are highly useful for predicting uneven temperature distribution inside a food tray, as illustrated in Figure 1. When cooling is not uniform, some regions of the food may remain in temperature zones that allow microbial growth even though other parts have already cooled. Numerical simulations based on the two-dimensional conduction–convection equations help identify how tray design, boundary conditions, and cooling duration influence the overall temperature profile. This approach provides a practical way to estimate safe and efficient cooling strategies without relying solely on physical experiments.

## 2. METHODS

Analytical solutions are often difficult to obtain for complex heat-transfer problems, particularly in two-dimensional transient systems with varying boundary conditions and non-uniform heat sources. Therefore, numerical approaches are employed to approximate the governing heat-transfer equations efficiently. In this study, the transient heat-conduction equation is solved using the explicit finite difference method implemented in MATLAB (Kafle et al., 2020). The computational domain represents an aluminum food tray with dimensions of  $20 \text{ cm} \times 15 \text{ cm}$ . The tray thickness is neglected, and the system is modeled as a two-dimensional transient heat-transfer problem. The food material is assumed homogeneous, with thermophysical properties of density  $\rho = 1050 \text{ kg}/\text{m}^3$ , specific heat capacity  $c_p = 3600 \text{ J}/\text{kg} \cdot \text{K}$ , and thermal conductivity  $k = 0.5 \text{ W}/\text{m} \cdot \text{K}$ .

The initial temperature of the localized food regions is set to  $80 \text{ }^\circ\text{C}$ , while the aluminum tray and surrounding air are initialized at ambient temperature ( $20 \text{ }^\circ\text{C}$ ). Three hot-food regions are introduced into the computational domain to represent localized heat sources within the tray.

The finite difference method works by breaking space and time into a grid of discrete points. The partial derivatives in the heat conduction–convection equation are then replaced with numerical approximations. For example, the second derivative in the x-direction can be written as:

$$\frac{\partial^2 T}{\partial x^2} \approx \frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{(\Delta x)^2} \quad (3)$$

The transient heat equation is solved using the explicit finite difference formulation:

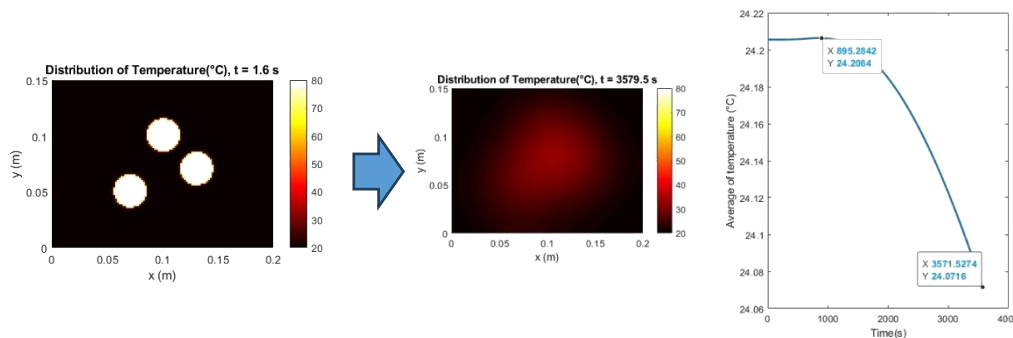
$$T_{i,j}^{n+1} = T_{i,j}^n + \frac{k}{\rho c_p} \Delta t \left( \frac{T_{i+1,j}^n - 2T_{i,j}^n + T_{i-1,j}^n}{(\Delta x)^2} + \frac{T_{i,j+1}^n - 2T_{i,j}^n + T_{i,j-1}^n}{(\Delta y)^2} \right) \quad (4)$$

This formulation provides a practical approach for tracking transient heat diffusion across the tray domain. Convective cooling is applied at all tray boundaries using Newton’s cooling law in Eq. (2). To represent localized air-cooling effects and non-uniform air exposure around the tray, different convective heat-transfer coefficients are assigned to each boundary. The upper boundary is assigned  $h = 40 \text{ W/m}^2\text{K}$ , the lower boundary  $h = 10 \text{ W/m}^2\text{K}$ , and the left and right boundaries  $h = 20 \text{ W/m}^2\text{K}$ . Here,  $T_s$  represents the transient surface temperature at the tray boundary, while  $T_\infty$  denotes the ambient air temperature, assumed to be  $20 \text{ }^\circ\text{C}$ . The computational domain is discretized into  $120 \times 90$  spatial nodes, resulting in grid spacings of  $\Delta x \approx 1.68 \times 10^{-3} \text{ m}$  and  $\Delta y \approx 1.69 \times 10^{-3} \text{ m}$ . The time step is selected as approximately 30% of the maximum stable time increment determined from the explicit finite difference stability criterion, resulting in  $\Delta t \approx 1.61 \text{ s}$ . The transient simulation is performed for a total duration of 1 hour (3600 s).

The computational domain is discretized uniformly in both spatial directions, and the selected time step satisfies the stability criterion of the explicit finite difference scheme. MATLAB is employed to solve the numerical model and visualize the transient heat-transfer behavior through surface plots and graphs of domain-averaged temperature decay and cooling rate over time. Finite difference based simulations provide an efficient tool for evaluating the thermal behavior of food systems in a comprehensive way (Nasser eddine et al., 2025). In this study, the tray domain is divided into a spatial grid containing three localized hot-food regions representing initially heated food portions. Heat then diffuses outward through conduction while gradually decreasing due to convective cooling at the boundaries. The thermophysical properties, including thermal conductivity, density, and specific heat capacity, are selected from representative values for aluminum trays and common food materials used in the Makan Bergizi Gratis (MBG) program. Three simulation scenarios are investigated to analyze how different hot-food placements influence transient temperature distribution and cooling behavior.

### 3. RESULT AND DISCUSSION

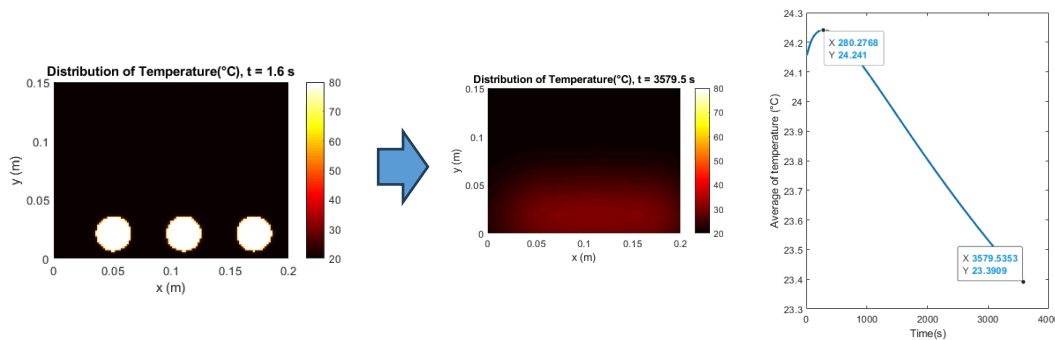
In closed food-container systems, conduction and convection are the dominant heat-transfer mechanisms governing thermal diffusion and cooling behavior (Algwauish et al., 2023). Based on these mechanisms, three simulation cases are investigated to evaluate the influence of hot-food placement on transient heat distribution inside the tray. The localized hot-food regions are arranged at the tray center, near the lower boundary, and near the tray edges, producing different thermal-distribution and cooling characteristics.



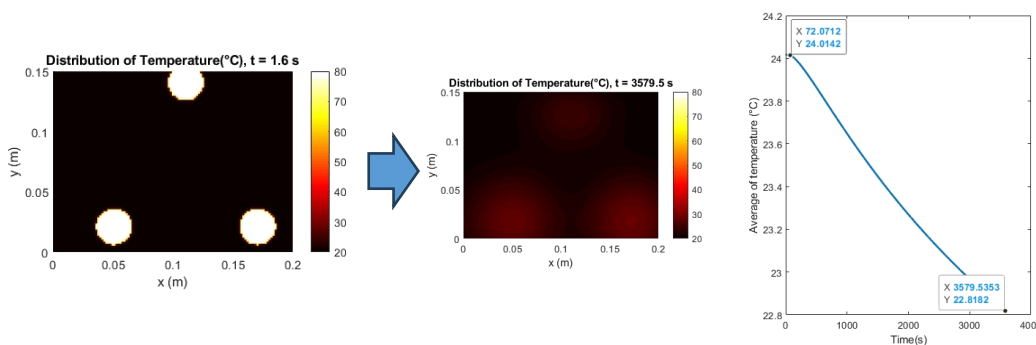
**Figure 2.** Case 1: the initial condition shows three hot food regions placed at the center of the tray (left), the final temperature distribution after cooling (middle), and the average tray temperature over time (right).

In the first case shown in Fig. 2, the hot food regions are positioned near the center of the tray, with an initial food temperature of 80 °C, while the aluminum tray and surrounding air are initialized at ambient temperature (20 °C). As heat diffuses from the localized hot-food regions into the cooler surrounding domain, the domain-averaged temperature initially increases and reaches a peak of 24.2 °C at 895 seconds (approximately 15 minutes). After this stage, convective cooling becomes dominant, causing the average temperature to gradually decrease to 24.07 °C at 3,571 seconds (around 59.5 minutes), corresponding to an average cooling rate of approximately  $-0.003$  °C/minute. The analysis focuses on the first hour of cooling to evaluate how the placement of food influences the resulting heat-distribution pattern.

In the second case, shown in Fig. 3, the hot-food regions are positioned near the bottom of the tray, while the tray and surrounding air remain at the ambient temperature of 20 °C. Heat initially accumulates along the lower section of the tray before gradually diffusing upward into the surrounding cooler domain. As a result, the domain-averaged temperature rises more rapidly and reaches a peak value of 24.24 °C at 280 seconds (approximately 4.6 minutes). After this stage, the temperature decreases continuously due to convective cooling, reaching 23.39 °C at 3,579 seconds. This corresponds to an average cooling rate of approximately  $-0.015$  °C/minute after the peak temperature is reached. Compared with Case 1, the lower average temperature observed after one hour indicates that heat dissipates more rapidly when the hot-food regions are located near the lower boundary of the tray.



**Figure 3.** Case 2: the initial condition shows three hot food regions placed at the bottom of the tray (left), the final temperature distribution after cooling (middle), and the average tray temperature over time (right).



**Figure 4.** Case 3: The initial condition shows three hot food regions distributed across the tray (left), the final temperature distribution after cooling (middle), and the average tray temperature over time (right).

In the third case, shown in Fig. 4, the hot-food regions are positioned near the edges of the tray, while the tray and surrounding air are initialized at the ambient temperature of 20 °C. Because the hot regions are located closer to the boundaries exposed to convective cooling, heat dissipates more rapidly into the surrounding environment. As a result, the domain-averaged temperature reaches its peak value of 24.01 °C very quickly, at only 72 seconds (approximately 1 minute). Afterward, the temperature decreases steadily and reaches 22.82 °C at approximately one hour, which is the lowest value among the three simulated cases. The corresponding average cooling rate after the peak temperature is approximately  $-0.020$  °C/minute. These results indicate that positioning the hot food near the tray

perimeter accelerates heat loss, whereas placing the food closer to the center helps maintain thermal uniformity and retain heat more effectively during the cooling process.

A comparison of the cooling rates shows clear differences in thermal behavior among the three configurations. Case 1, where the hot-food regions are positioned near the center of the tray, exhibits the slowest cooling rate ( $-0.003$  °C/minute), indicating better heat retention and more stable thermal distribution. In contrast, Case 2 produces a faster cooling rate ( $-0.015$  °C/minute) due to the proximity of the hot regions to the lower boundary, which enhances heat dissipation. The fastest cooling occurs in Case 3 ( $-0.020$  °C/minute), where the hot-food regions are placed near the tray edges, allowing heat to escape more efficiently through the boundaries exposed to convective cooling. These results demonstrate that the spatial placement of food significantly influences the cooling behavior and thermal uniformity inside the tray.

Research on heat distribution in metals has long been an important topic in thermal engineering, as their high thermal conductivity strongly influences how quickly and uniformly heat spreads. Temperature differences in metal plates can drop rapidly because metals conduct heat very efficiently (Xu et al., 2019). This principle is relevant for materials like aluminum commonly used in food trays which can distribute heat evenly across their surface, allowing local temperature changes to spread quickly. Studies also show that temperature variations and metal type affect conduction rates, with aluminum exhibiting a higher heat transfer rate compared to brass and iron (Sari et al., 2023). To provide insight and predictive analysis for heat behavior in food trays, this study models heat distribution in an aluminum tray under conditions similar to those observed in the Makan Bergizi Gratis (MBG).

#### 4. CONCLUSION

This study presents several transient heat-transfer simulation scenarios to examine how food placement influences temperature distribution and cooling behavior inside an aluminum food tray. The results show that food positioned near the center of the tray produces a more balanced thermal distribution and slower heat dissipation compared with food placed near the lower boundary or tray edges. In Case 1, where the hot-food regions are located near the center, the cooling rate is approximately  $-0.003$  °C/minute, indicating better heat retention and greater thermal stability. In contrast, Case 2 and Case 3 exhibit faster cooling rates of approximately  $-0.015$  °C/minute and  $-0.020$  °C/minute, respectively, due to increased exposure to convective cooling at the tray boundaries.





These findings demonstrate that the spatial arrangement of food significantly affects transient heat diffusion, thermal uniformity, and cooling performance inside the tray. Food positioned closer to the tray center retains heat more effectively, whereas food located near the boundaries loses heat more rapidly due to stronger convective heat transfer. Beyond the present simulation scenarios, the numerical approach developed in this study shows potential for evaluating additional thermal factors in food-distribution systems. Future work may extend the model to more realistic three-dimensional tray geometries, varying food quantities, or different food thermophysical properties such as moisture content, density, and initial temperature. Such developments may contribute to safer and more efficient food-storage and distribution systems, particularly in large-scale meal-service programs such as Makan Bergizi Gratis (MBG).

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