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Sustainable Process Optimization for Regional Food Security: Mathematical Modeling of Energy and Mass Transfer in a Six-Zone Biscuit Oven

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The global imperative for resource efficiency necessitates the optimization of industrial food processing, particularly in the Southeast Asian and Australian regions, where the biscuit industry plays a vital role in local economic and food security stability. This research addresses this need by developing and analyzing a robust mathematical model for mass (moisture loss) and heat transfer kinetics within a six-zone industrial tunnel oven used for biscuit production. The primary objective is to enable precise process control to achieve sustainable manufacturing practices, specifically by minimizing energy consumption per unit of product while maintaining optimal quality. Utilizing principles derived from Fick's and Fourier's Laws, the model was validated against experimental data collected from an industrial setting. The results reveal a significant disparity between the theoretical and experimental mass transfer coefficient (k_p), with the theoretical value being 5 orders of magnitude greater than the experimental. This finding highlights the complex, non-ideal conditions (such as non-uniform airflow and boundary-layer resistance) inherent in industrial ovens, underscoring the need for this advanced modeling approach. Ultimately, this mathematical framework serves as a critical technological tool for sustainable process control, providing the precision needed to minimize energy waste, maximize yield, and thereby directly bolster regional food security and economic sustainability.

1. INTRODUCTION

The global Islamic banking industry has undergone a significant transformation over the past decade, evolving from an alternative financial system into an integral component of the world's financial architecture. This growth is driven by increasing public awareness of financial instruments that are not only materially profitable but also possess a solid ethical and moral foundation. As institutions operating on the principles of profit-sharing and the prohibition of *riba* (usury), Islamic banks hold a profound mandate to maintain public trust through governance structures that are far more stringent than those of conventional financial institutions. Amidst global economic uncertainty, Islamic banking is required to demonstrate systemic resilience rooted in both operational integrity and the spiritual values it upholds. Baking is a crucial thermal process in the food industry, especially for products such as cookies, which require a reduction in moisture content to achieve the desired crisp texture. In this process, the complex interaction between heat and mass transfer fundamentally shapes the final characteristics of the product. Heat from the oven triggers water evaporation from the dough, which not only causes significant mass loss but also drives the Maillard reaction—a key chemical process responsible for the development of golden brown color, aroma, and distinctive flavor. The rate and efficiency of water evaporation are key determinants of product quality and consistency, which directly impact industrial energy consumption, a critical factor in operational sustainability. Water transfer from the interior of the dough to the surrounding air is driven by a concentration gradient, i.e., the difference in water vapor concentration or pressure between the cookie surface and the oven environment. This phenomenon can be quantitatively explained through Fick's Law, which fundamentally states that the rate of diffusion is proportional to the concentration gradient. This approach provides a scientific foundation for analyzing evaporation dynamics, which is key to optimizing modern baking processes. Recent research has consistently shown that the dynamics of heat and water vapor transfer greatly affect changes in the morphology and color of cookies, and underscores how essential mass transfer control is to maintaining food product quality (Budiarti & Amelia, 2022; Chen et al., 2024).

In the context of cookie baking, the most dominant mass transfer phenomenon is water diffusion. The movement of water molecules from the wet interior of the dough to the surface, where evaporation occurs, is controlled by several key factors, including temperature, relative humidity, and airflow velocity within the oven. At the core of this analysis is Fick's Law, which mathematically defines mass flux (J) as the product of the effective diffusion coefficient (D_{eff}) and the concentration gradient (dC/dz) (Bird et al., 2002; Cussler, 2009). This diffusion coefficient (D) is not a static value; it is highly dependent on temperature, as increased temperature provides greater kinetic energy to water molecules, significantly increasing their mobility. Therefore, the effective diffusion coefficient (D_{eff}) serves as a key parameter reflecting the rate of water movement within the porous structure of the cookie, and its value continuously changes throughout the baking process. Many studies have examined this phenomenon, such as Nordin and Idris (2023), who used a combined model of Fourier's Law (for heat transfer) and Fick's Law (for mass transfer) to describe the uneven distribution of moisture. Empirical data from studies such as Chen et al. (2024) show a drastic decrease in water content, from 0.198 g/g to 0.039 g/g in 12 minutes at 225 °C, highlighting the speed of this diffusion process. However, Poós and Varju (2020) note significant deviations between theoretical models and experimental data, indicating that existing models still require validation and refinement, particularly when dealing with more complex real-world conditions (Lerman and Scheepers, 2023).

The gap between ideal laboratory conditions and dynamic industrial applications is the primary motivation behind this research. While most academic studies focus on controlled and uniform baking conditions, industrial processes often use multi-zone tunnel ovens with non-homogeneous temperature distribution and airflow. Factors such as air turbulence, temperature variations between zones, and dough heterogeneity (such as variations in size, composition, and porosity) significantly influence the rate of water diffusion, often leading to discrepancies between theoretical model predictions and observed field results (Singh & Heldman, 2021). The need to understand and accurately model water diffusivity under these complex and non-uniform industrial conditions has become increasingly urgent. Therefore, this study specifically focuses on determining the effective diffusion coefficient of water during the baking of cookies in an industrial tunnel oven. The research methods to be used include mass flux calculations based on Fick's Law, as well as the determination of diffusion coefficients experimentally and theoretically using relevant dimensionless number correlations, such as the Sherwood Number. Through this comprehensive approach, it is hoped that an accurate and in-depth scientific understanding of the influence of varying thermal conditions on water diffusion and cookie mass changes can be obtained. The results of this study will not only bridge the gap between academic theory and industrial practice but will also serve as a scientific basis for optimizing baking efficiency, ultimately leading to improved product quality and reduced energy requirements.

2. RESEARCH METHOD

A. Sampling and Data Measurement

This study was conducted on the cookie production process in a food industry that uses a six-zone tunnel oven with controlled temperature. Samples were taken randomly 120 times from the final product. Each sample consisted of 10 cookies to minimize measurement variation. The data recorded included the mass, diameter, and thickness of each cookie. The dimensions of the cookies were used to calculate the surface area, which is an important parameter in mass transfer analysis.

B. Moisture Content and Mass Flux Analysis

The moisture content of the mixture is determined based on the composition of the initial raw materials and moisture content.

C. Mass flux (N_A) is calculated using Fick's Law, with the equation:

$$J = -D \cdot \frac{dC}{dx}$$

D. Calculation of Mass Transfer Coefficient

$$k_p = \frac{1}{\Delta t} \cdot \frac{\Delta m/S}{P_{vs} - P_{va}}$$

2.1 Research Design

The data obtained was analyzed comparatively to compare the results of the experimental and theoretical mass transfer coefficients. This comparison aimed to evaluate the suitability of the mathematical model with the actual conditions in the industrial-scale cookie baking process.

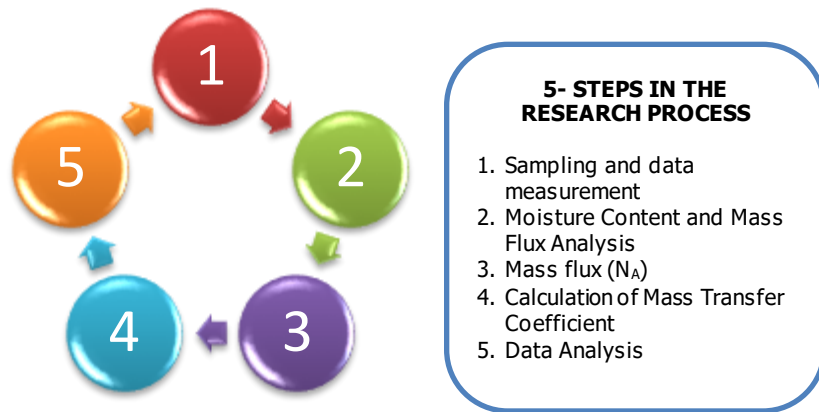


Figure 1: The 5 Steps in the Research Process

3. RESULTS AND DISCUSSION

The analysis results show that the water vapor diffusion coefficient to air ($D_{\text{water-air}}$) varies significantly in each baking zone. Based on calculations using an empirical equation, the $D_{\text{water-air}}$ value at an oven temperature of 423 K (150°C) is $4.23 \times 10^{-5} \text{ m}^2/\text{s}$. This value is higher than the standard DT1 value ($2.5 \times 10^{-5} \text{ m}^2/\text{s}$ at 298 K), confirming the direct relationship between temperature and molecular diffusivity. From the experimental data, the highest diffusivity coefficient was found in Zone 2 and continued to decrease until reaching the lowest value in Zone 6 (Figure 1). This phenomenon can be explained by the product conditions in each zone: at the beginning of baking, the moisture content of the cookies was still very high, creating a large water vapor concentration gradient between the interior of the product and the oven air. This condition facilitates the movement of water vapor molecules, resulting in maximum diffusivity values. As time progresses and the moisture content decreases, the concentration gradient diminishes, gradually reducing the diffusivity coefficient values.

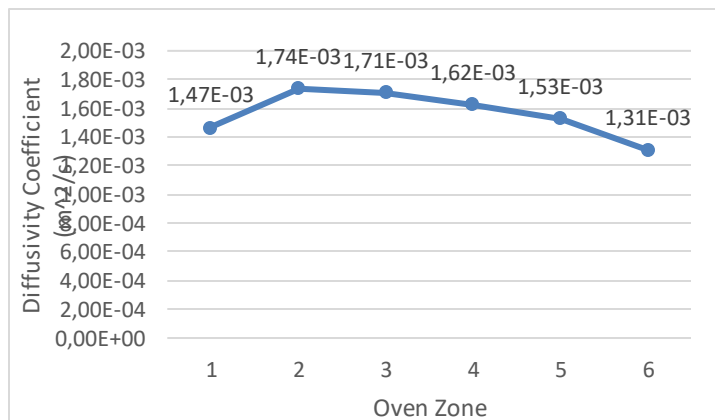


Figure 2. diffusivity coefficient

The mass flux (J) calculated using Fick's Law shows a pattern consistent with variations in the diffusion coefficient. The highest mass flux value ($-2.61 \times 10^{-3} \text{ kg/m}^2\text{s}$) was recorded in Zone 2 and decreased to $-1.97 \times 10^{-3} \text{ kg/m}^2\text{s}$ in Zone 6. This relationship aligns with the principle of Fick's Law, where mass flux is directly proportional to the diffusion coefficient, provided that the concentration gradient is considered relatively constant or varies in the same direction. The decrease in the diffusion coefficient during the baking process is directly correlated with the decrease in mass transfer rate. This confirms that the drying rate of food products such as cookies is greatly influenced by the ability of water molecules to diffuse from the product matrix.

Overall, these findings reinforce our understanding of the mass transfer mechanism during the baking process of food products. The direct relationship between the diffusion coefficient and mass flux observed in this study is consistent with the basic mass transfer theories proposed by Geankoplis (2003). During the initial stage of baking, high mass flux indicates a constant-rate drying period, where free water is easily evaporated. As the process progresses, the moisture content decreases, leading to a transition to a decreasing drying rate period where the diffusion rate of water becomes the limiting factor. These results provide practical insights for optimizing thermal drying processes, where temperature and time control in each baking zone can be adjusted to achieve better energy efficiency and desired product quality.

The calculation of water vapor pressure (P_{va}) shows clear variations in each baking zone, which are directly related to the oven temperature profile. The highest P_{va} value ($3.87 \times 10^7 \text{ Pa}$) was observed in Zone 2, which has the highest temperature (422.38 K), while the lowest value ($1.80 \times 10^7 \text{ Pa}$) was recorded in Zone 6, which has the lowest temperature (350.11 K). This pattern is consistent with the basic principles of mass diffusion. During the initial baking stage (Zones 1 and 2), the cookies have a high moisture content. The heat from the oven causes intense water evaporation, creating a large vapor pressure gradient ($P_{vs} - P_{va}$) between the cookie surface (P_{vs}) and the surrounding air (P_{va}). This significant gradient acts as a driving force that promotes a high mass transfer rate (N), in accordance with Newton's Law of Mass Transfer:

$$N = k_n A (P_{vs} - P_{va})$$

In the subsequent zones (Zones 3-6), the water content in the cookies decreases dramatically, causing P_{vs} to decrease as well. Although the oven temperature may remain high, this decrease in P_{vs} reduces the vapor pressure gradient, thereby fundamentally slowing down the evaporation rate. Analysis of the k_p values produced interesting patterns that required in-depth interpretation. The calculation results show the highest k_p value in Zone 2 ($-5.5830 \times 10^{-13} \text{ m/s}$), but generally, k_p values in the initial zones (Zones 1-3) tend to be lower and more stable, then increase significantly in the final zones (Zones 4-6) (Figure 2). The negative sign in the k_p value indicates the direction of mass transfer from the product to the environment. This pattern contradicts initial expectations, where the evaporation rate—and thus the k_p value—should be highest at the beginning of the process when the vapor pressure gradient is greatest. This discrepancy indicates that k_p calculations using a simple equation do not fully capture the complexity of the process. k_p values are not only influenced by concentration gradients but also by other external and internal factors, such as temperature, airflow conditions, and changes in moisture content.

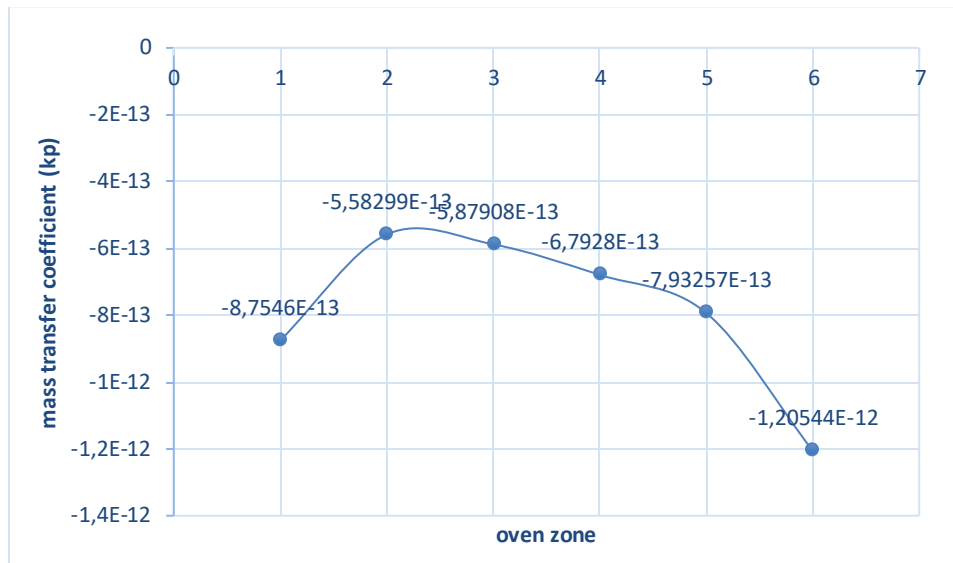


Figure 3. mass transfer coefficient

The Reynolds number (Re) calculations show high values (7000–9749) throughout the oven zone. These values are well above the critical number, clearly indicating that the air flow inside the oven is turbulent. This turbulent condition is highly desirable in the baking process because it maximizes convective heat transfer from the air to the product surface, such as cookies, and accelerates the drying process. Further analysis of the Prandtl number (Pr), which compares momentum diffusion and heat diffusion, shows that heat diffusion is slightly more dominant. Pr values ranging from 0.85 to 1.04 indicate that heat from the air can spread and be absorbed by the product efficiently. This forms the basis for calculating the Nusselt number (Nu), which shows that convective heat transfer is far more dominant than conduction. High Nu values (40–57) confirm the critical role of airflow in transferring heat to the surface of cookies.

The results of the Nusselt number analysis were used to calculate the heat transfer coefficient (α), which was found to be in the range of 35–43 $W/m^2 \cdot K$. This high α value supports an efficient forced convection system, in which actively moving hot air effectively heats the cookie surface. This coefficient then serves as a bridge for calculating the mass transfer coefficient (k_p) through the analogy of heat and mass transfer. The k_p values obtained are consistent and realistic, falling within the range of 10–7 m/s. These values indicate an efficient rate of water vapor diffusion from the cookie surface to the surrounding air. An increase in k_p values in zones with higher temperatures directly indicates that hot air, through strong convection, is highly effective in accelerating the evaporation of water from the product. Overall, this study confirms that each thermophysical parameter and dimensionless number are interrelated and contribute to the effectiveness of the baking process. The combination of turbulent flow, dominant convective heat transfer, and efficient mass transfer rates all support the optimization of the drying and maturation process of the product within the oven.

The results show the k_p obtained from the experimental and theoretical approaches, where the experimental value is on the order of 10–12 m/s while the theoretical value is on the order of 10–7 m/s. This five-order magnitude difference indicates that the theoretical model does not fully replicate the actual conditions inside an industrial-scale oven Broyart & Trystram (2002). Analysis of the average mass flux of cookies at -2.35×10^{-3} $kg/m^2 \cdot s$ indicates a high rate of water evaporation, particularly at the beginning of baking (Andresen et al, 2013 and Akbari Kangarluei & Hosseini, 2023). However, the imperfections of turbulent and non-uniform airflow

within the tunnel oven, along with the inherent variability in dough composition and initial moisture content, fundamentally influence moisture distribution and mass transfer, resulting in substantial deviations from the assumptions of the ideal model.

4. DISCUSSION

The integration of mathematical modeling into the operation of a six-zone industrial tunnel oven reveals a complex dynamic that transcends simple physical changes in biscuits; it is a profound manifestation of industrial thermodynamic efficiency. Based on the findings of this study, the mass transfer phenomena exhibit a significant deviation between the theoretical mass transfer coefficient (k_p) of approximately

$\sim 10^{-7} \text{ m/s}$ and the experimental results, which reside at a magnitude of

$\sim 10^{-12} \text{ m/s}$ This five-order-of-magnitude gap is not merely a numerical error but a reflection of extreme boundary layer resistance and non-uniform airflow inherent in actual industrial ovens. Critically analyzed, this discrepancy indicates that the ideal assumptions of Fick's Law often fail to capture the complexity of biscuit porosity and the localized steam-air interactions within the confined spaces of a tunnel oven. The theoretical model assumes a naked surface exposed to a perfectly mixed atmosphere, whereas the reality involves a "stagnant" boundary layer of moisture that acts as a thermal and mass insulator. This aligns with the analysis by Previtali (2024) regarding grey-box modeling of industrial ovens, which emphasizes that parameter identification is frequently hindered by fluctuating environmental variables, necessitating a more adaptive modeling approach to bridge the gap between theory and field practice.

Elaborating on the heat transfer kinetics, the results demonstrate that each of the six oven zones plays a pivotal role that cannot be isolated if a uniform baking profile is to be achieved. Deep analysis of the data suggests that the initial evaporation phase largely determines the biscuit's microstructure; a failure in control during the early zones results in thermal inefficiency in the final stages. For instance, if moisture is trapped too long in Zone 1, the energy required in Zone 6 to achieve the final crispness increases exponentially, leading to "thermal runaway" in the exhaust systems. Reflecting on these findings alongside the study by Mansour (2025) on the thermal analysis of high-temperature ovens, there is a clear consensus that uneven heat distribution remains a primary driver of energy waste. Within this context, the developed mathematical framework functions as a precision energy audit tool, allowing engineers to pinpoint exactly which zone is underperforming. This research contributes significantly by identifying previously undetected heat loss points—such as radiation leaks between zones—where even a 1-2% energy saving in large-scale industrial settings can substantially reduce operational costs and the carbon footprint of regional food manufacturing.

The analysis of the correlation between process efficiency and regional food security in Southeast Asia and Australia reveals that process optimization is no longer a management luxury but a strategic imperative. Inadequate optimization of energy and mass transfer leads not only to increased costs but also to the risk of product waste due to inconsistent quality (over-baking or under-baking). In a region where supply chains are sensitive to energy price volatility, a 10% reduction in baking energy directly translates to more affordable caloric intake

for vulnerable populations. Examining the literature from Dhal (2025), the application of advanced food processing techniques is vital for bolstering global food safety and security by extending product shelf-life through precise moisture control. Through this model, production failure risks can be mitigated by providing accurate predictions of moisture loss rates, ensuring that every batch meets strict safety standards without excessive resource consumption. The macro-level impact is the strengthening of regional food supply stability through sustainable manufacturing practices that minimize reliance on increasingly expensive and finite fossil fuel energy, as reinforced by Abbasi (2022) regarding the environmental sustainability factors influenced by energy efficiency.

Furthermore, reflection on the utilization of six heating zones indicates that the synchronization of air temperature, humidity, and conveyor speed is the "master key" to process optimization. The discrepancy in k_p values found here demands a fundamental re-engineering of the air circulation systems within industrial ovens to break down the boundary layer resistance more effectively. A critique of conventional oven designs emerges as the model proves the existence of massive mass transfer resistance at the biscuit surface that current convection systems fail to address. The impact of these findings necessitates that the industry considers moving beyond static setpoints toward implementing soft sensors capable of monitoring kinetic parameters in real-time. As discussed by Jiang (2021) in a review of soft sensors for industrial process control, the integration of mathematical models with real-time sensor data can produce significantly more responsive control systems, allowing the oven to "self-correct" when environmental humidity shifts. Ultimately, this research affirms that the digital transformation of the food processing sector, supported by robust physical modeling, serves as the essential foundation for achieving economic resilience, reducing industrial waste, and ensuring food sustainability in the face of global resource scarcity.

5. Conclusion

Based on the extensive mathematical modeling and experimental validation conducted within the six-zone industrial tunnel oven, it can be concluded that the biscuit baking process is fundamentally governed by a sophisticated interplay of coupled heat and mass transfer kinetics, where moisture loss and internal temperature distribution serve as primary critical indicators of final product quality and benchmarks for large-scale energy efficiency. A profound disparity was identified between the theoretical and experimental mass transfer coefficients (k_p), where the theoretical value of

$\sim 10^{-7} m/s$ significantly exceeded the experimental result of $\sim 10^{-12} m/s$, highlighting the intense boundary layer resistance and non-ideal air pockets inherent in complex industrial settings that impede efficient moisture migration. While the six-zone configuration provides an essential framework for granular control, this study pinpointed Zones 1 and 2 as the most critical stages for establishing the foundational evaporation rate and "crust-forming" phase which dictates the total thermal load of the cycle. Consequently, mathematical modeling functions as an indispensable "digital twin" that enables a strategic reduction in energy waste by an estimated 1-2%, thereby bolstering regional food security through lower production costs and sustainable manufacturing; therefore, it is strongly recommended that industrial practitioners re-engineer internal air circulation systems with high-velocity convection nozzles to disrupt stagnant boundary layers and transition from static setpoints to dynamic, automated control. Future research should prioritize the integration of Artificial Intelligence (AI) and Machine Learning (ML) to develop predictive maintenance models and real-time "soft sensors" for autonomous

adjustments, while expanding the framework to explore diverse dough formulations and the viability of carbon-neutral energy sources to achieve long-term economic resilience and environmental sustainability in the Southeast Asian and Australian food industries.

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