

Heat and Mass Transfer in Food Systems: Fundamentals, Coupled Mechanisms, and Emerging Processing Technologies

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Abstract

Heat and mass transfer underpin food preservation, thermal processing, drying, cooling, and quality retention. In food matrices, conduction, convection, and radiation interact with moisture migration, vapor diffusion, solute movement, and phase change. These coupled processes influence temperature distribution, microbial inactivation, texture, nutrient retention, and energy use. This editorial summarizes the principal heat-transfer mechanisms, transient heating in packaged foods, and the interactions between thermal and mass transport. It also highlights the use of computational fluid dynamics and multiphysics modeling to examine spatial gradients, locate slow-heating regions, and support process design. Emerging technologies, including ohmic and other electric-field processing, may offer faster volumetric heating in suitable foods, although field uniformity, equipment design, and process validation remain important challenges. Integrating sound transport models with experimental validation can help develop food processes that are safe, energy-conscious, and capable of preserving product quality.

Keywords: Heat Transfer; Mass Transfer; Food Processing; Thermal Diffusivity; Computational Fluid Dynamics; Ohmic Heating

Introduction

Heat and mass transfer govern many food-processing operations, including drying, cooling, freezing, pasteurization, sterilization, and packaging. They affect food safety and shelf life as well as nutritional value, texture, and flavor [1,2]. In biological materials, conduction, convection, and radiation interact with moisture migration, vapor diffusion, capillary flow, and solute movement. Because foods are heterogeneous, porous, and compositionally complex, these processes commonly occur simultaneously and may be nonlinear [3,4]. Predicting temperature distributions and moisture movement therefore remains a central challenge in food process engineering.

In thermal processing, non-uniform heating can compromise microbial safety, whereas excessive heating may damage quality. During drying, baking, and dehydration, internal moisture gradients alter local thermal properties and transport rates. Integrated heat-mass transfer models can help describe these interactions and support process optimization. Computational fluid dynamics (CFD), Multiphysics simulation, and digital modeling increasingly enable researchers to predict transport behavior in complex food systems [16,17].

Ohmic heating and moderate electric-field processing are among the technologies being investigated to improve energy delivery and reduce processing time. Their performance depends on food composition, electrical properties, equipment configuration, and field distribution; product safety and quality must still be demonstrated for each application [17]. This editorial reviews fundamental transport mechanisms, transient heating in packaged foods, coupled heat and mass transfer, and the potential contribution of modeling and emerging processing technologies.

Fundamental heat-transfer mechanisms in food systems

Thermal energy is transferred by conduction, convection, and radiation. These mechanisms may operate simultaneously, depending on the food properties and processing conditions [5,6]. The three modes are summarized schematically in figure 1.

Conduction

Conduction transfers energy through molecular interactions without bulk movement of the material and is often important in solid and semi-solid foods [1,2]. Fourier's law can be expressed as:

$$q'' = -k (dT/dx)$$

Thermal conductivity depends on composition, temperature, moisture content, porosity, and structure. In general, air-filled pores reduce effective thermal conductivity relative to water-rich regions [3,4].

Convection

Convection transfers heat between the surface and a moving fluid, or within a fluid through bulk motion. Forced convection is driven by an external device, whereas natural convection arises from buoyancy forces associated with density differences [5]. Newton's law of cooling is commonly written as:

$$q'' = h(T_s - T_\infty)$$

In liquid foods heated in cans or retort containers, natural convection can create circulation patterns and influence the location of the slowest-heating region [7].

Radiation

Radiative heat transfer occurs through electromagnetic waves and does not require a material medium. It is relevant to infrared heating and contributes to heat transfer in baking and drying [8]. The Stefan-Boltzmann relationship for an idealized radiating surface is:

$$q'' = \varepsilon \sigma (T_s^4 - T_{sur}^4)$$

Surface emissivity and the temperature difference between the surface and its surroundings influence radiative heat exchange. The effect of radiation should be considered alongside convection and conduction rather than treated as a universal explanation for rapid surface heating.

Transient heating in packaged foods

Thermal processing of canned foods and retort pouches is transient: temperature varies with time and position within the product and package [2,9]. Figure 2 illustrates a conceptual temperature field and the slowest-heating region in a retort container.

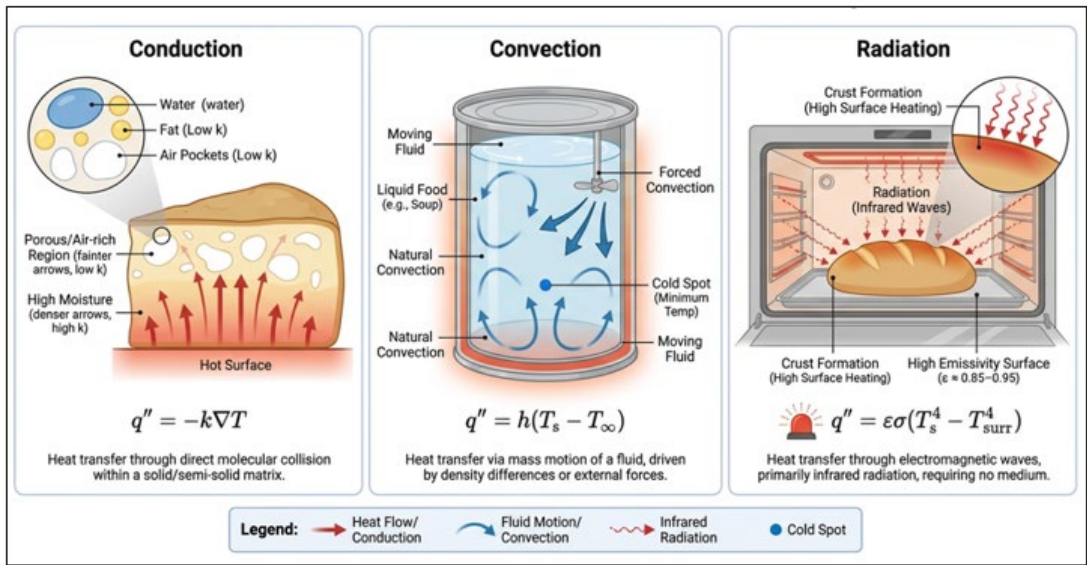


Figure 1: Fundamental heat-transfer mechanisms in food systems: conduction, convection, and radiation.

For a homogeneous, isotropic solid with constant thermal properties and no internal heat generation, the transient heat-conduction equation is:

$$\partial T / \partial t = \alpha \nabla^2 T$$

Here, α is thermal diffusivity ($\text{m}^2 \text{s}^{-1}$). The Biot number ($\text{Bi} = hL/k$) compares internal conductive resistance with external convective resistance, while the Fourier number ($\text{Fo} = \alpha t/L^2$) represents dimensionless time.

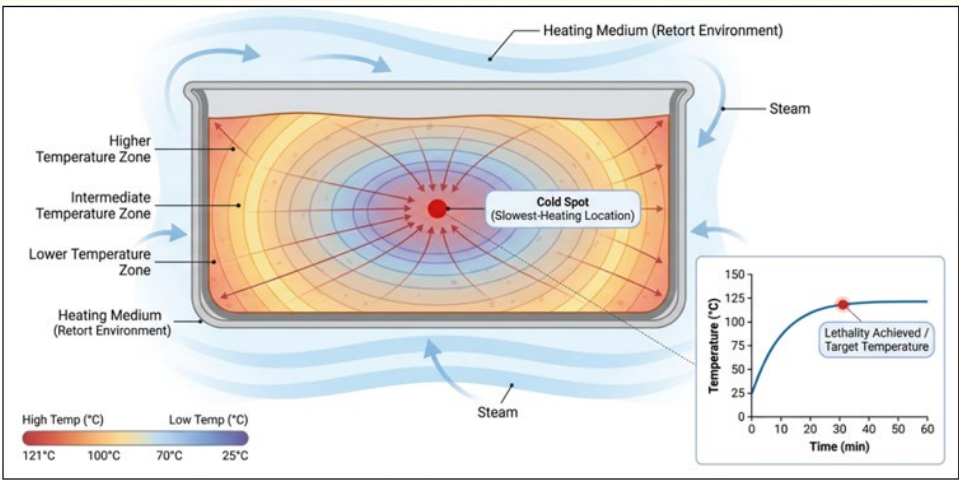


Figure 2: Conceptual temperature distribution and slowest-heating region in a packaged food container during retort processing.

Thermal lethality

$$F_0 = \int_0^t 10^{(T(\tau) - T_{ref})/z} d\tau$$

$$F_0 = \int_0^t 10^{\frac{T(t)-T_{ref}}{z}} dt$$

Coupled heat and mass transfer

Heat and mass transfer are coupled: temperature gradients can drive evaporation and vapor movement, while moisture migration and phase changes alter local enthalpy, structure, and effective transport properties [3,4].

Mass-transport mechanisms

Moisture and solutes may move through liquid diffusion, capillary flow, vapor-phase diffusion, and pressure-driven flow. Fick’s second law is often used for diffusion-dominated transport, while more comprehensive porous-media models may be needed when flow and phase change are important [10]. Evaporation also removes latent heat from the product surface:

$$\partial M/\partial t = \nabla \cdot (D_{eff} \nabla M)$$

Drying may shift from a period in which surface evaporation controls the rate to a falling-rate period in which internal moisture transport becomes limiting. Crust formation and structural changes can contribute, but the transition depends on the food and drying conditions [11].

Comparative analysis of transport mechanisms and food properties table 1 compares dominant heat- and mass-transfer mechanisms across selected operations, while table 2 provides illustrative thermophysical values for selected food components.

Operation Mode	Dominant Heat Mechanism	Dominant Mass Mechanism	Governing Parameters	Typical Industrial Examples
Retort Sterilization	Conduction / Natural Convection	Minimal internal mass transfer	Heat-transfer coefficient; retort temperature; package geometry; Bi and Fo	Canned meats, pouch meals
Hot-Air Dehydration	Convection and Radiation	Liquid Diffusion and Vapor Gradients	Air temperature and velocity; relative humidity; moisture diffusivity	Sliced fruits, vegetables
Deep-Fat Frying	Convection and Conduction	Vapor Transport and Oil Adsorption	Oil temperature; frying time; porosity; vapor pressure; oil uptake	Potato chips, french fries
Baking	Radiation and Convection	Internal Vaporization and Diffusion	Oven temperature; air velocity; moisture diffusivity; surface heat-transfer coefficient	Bread, pastry products
Freeze-Drying	Conduction / IR Radiation	Ice Sublimation and Porous Flow	Pressure; shelf temperature; product temperature; vapor pressure; pore structure	Coffee extracts, berries

Table 1: Comparative matrix of transport mechanisms in food-processing operations.

Food material/component	Moisture content (% wet basis)	Thermal conductivity, k ($\text{W m}^{-1} \text{K}^{-1}$)	Thermal diffusivity, α ($\times 10^{-7} \text{m}^2 \text{s}^{-1}$)	Effective moisture diffusivity, D_{eff} ($\text{m}^2 \text{s}^{-1}$)
Pure Water []	100	0.598	1.43	N/A
Ice []	100	2.250	11.80	N/A
Lean Beef Muscle	75-78	0.48-0.52	1.25-1.35	
Whole Milk	87	0.530	1.28	N/A
Potato Tissue	80	0.550	1.20-1.30	
Wheat Flour Dough	40-45	0.38-0.42	0.95-1.05	

Table 2: Illustrative thermophysical properties of selected food components.

Emerging technologies and computational modeling

CFD and multiphysics finite-element approaches can help estimate temperature fields, identify slow-heating zones, and assess the effects of package geometry and process conditions [12,17]. Volumetric heating approaches, including ohmic heating and radio-frequency or microwave processing, can reduce reliance on heat conduction from the surface toward the center. Their performance nevertheless depends on electrical or dielectric properties, geometry, and field uniformity [17].

Reliable food-process design requires transport models to be checked against suitable experimental data. Model predictions are sensitive to assumptions about geometry, material properties, boundary conditions, and phase change; therefore, simulated results should be interpreted within the validated range of conditions. Future work should connect mechanistic modeling with process monitoring and practical validation to improve safety, quality, and energy performance.

Bibliography

1. Bird RB., *et al.* "Transport phenomena". 2nd edition. John Wiley & Sons (2002).
2. Crank J. "The mathematics of diffusion". 2nd edition. Clarendon Press (1975).
3. Datta AK. "Porous media approaches to studying simultaneous heat and mass transfer in food processes. I: Problem formulations". *Journal of Food Engineering* 80.1 (2007): 80-95.
4. Datta AK. "Transport in porous media approach to modeling of food processing". *International Journal of Food Properties* 10.2 (2007): 231-266.
5. Fellows PJ. "Food processing technology: principles and practice". 4th edition. Woodhead Publishing (2017).
6. Ghani AG., *et al.* "Numerical simulation of natural convection heating of canned food by computational fluid dynamics". *Journal of Food Engineering* 41.1 (1999): 55-64.
7. Krishnamurthy K., *et al.* "Infrared heating in food processing: An overview". *Comprehensive Reviews in Food Science and Food Safety* 7.1 (2008): 2-13.
8. Ni H and Datta AK. "Moisture transport in porous food materials during heating: A multiphase porous media model". *Industrial and Engineering Chemistry Research* 37.11 (1998): 4461-4471.

9. Singh RP and Heldman DR. "Introduction to food engineering". 5th edition. Academic Press (2014).
10. Stoforos NG. "Thermal processing of packaged foods". In: Handbook of Food Processing: Food Preservation. CRC Press (2015): 211-245.
11. Gulati T and Datta AK. "Mechanistic understanding of case-hardening and texture development during drying of food materials". *Journal of Food Engineering* 166 (2015): 119-138.
12. Erdogdu F, *et al.* "Experimental determination and computational modelling of heat and mass transfer in food systems". *Trends in Food Science and Technology* 66 (2017): 124-134.
13. Rao MA, *et al.* "Engineering properties of foods". 4th edition. CRC Press (2014).
14. Tiwari BK, *et al.* "Novel thermal and non-thermal technologies for fluid foods". Academic Press (2011).
15. Chen S, *et al.* "Modeling and simulation of mass transfer in food processing: Recent advances in governing equations, workflow, and applications". *Foods* 15.12 (2026): 2084.
16. Szpicer A, *et al.* "Computational fluid dynamics simulation of thermal processes in food technology and their applications in the food industry". *Applied Sciences* 15.1 (2025): 424.
17. Bedane T, *et al.* "Recent advances in moderate electric field (MEF) systems for sustainable food processing". *Processes* 13.8 (2025): 2662.

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