ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

THE MULTIDISCIPLINARY JOURNAL OF SCIENCE AND TECHNOLOGY

VOLUME-6, ISSUE-3

IMPROVEMENT OF AN ENERGY-SAVING VIBRO-CONVECTIVE DRYER AND THE GARLIC DRYING PROCESS BASED ON ANSYS FLUENT MODELING

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Abstract: This paper addresses the improvement of an energy-saving vibro-convective drying unit and the garlic drying process based on numerical modeling in ANSYS Fluent. The study aims to justify design and operating solutions that intensify heat and mass transfer while reducing specific energy consumption. A CFD model of the drying chamber is developed using the Navier–Stokes equations coupled with energy and moisture/evaporation transport formulations and appropriate turbulence modeling; boundary conditions are defined by the drying-air parameters and product properties. The effects of air temperature and velocity, vibration-related parameters, slice thickness, and initial moisture content are investigated with respect to velocity and temperature fields, evaporation intensity, and flow stability within the product layer. The simulations reveal regions of non-uniform airflow and heat supply and provide guidance for optimizing air-distribution geometry and operating regimes to achieve a more uniform thermal field and faster moisture removal. The results can support the design and modernization of vibro-convective dryers for food materials, improving energy efficiency and final product quality.
Keywords: ANSYS Fluent, CFD modeling, vibro-convective drying, garlic, heat and mass transfer, energy efficiency, drying unit.

СОВЕРШЕНСТВОВАНИЕ ЭНЕРГОСБЕРЕГАЮЩЕЙ ВИБРО-КОНВЕКТИВНОЙ УСТАНОВКИ И ПРОЦЕССА СУШКИ ЧЕСНОКА НА ОСНОВЕ МОДЕЛИРОВАНИЯ В ANSYS FLUENT

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Аннотация: В статье рассматривается совершенствование энергосберегающей вибро-конвективной установки и процесса сушки чеснока на основе численного моделирования в программном пакете ANSYS Fluent. Цель работы — обосновать конструктивно-режимные решения, повышающие интенсивность тепло- и массообмена при одновременном снижении удельных энергозатрат. Для анализа газодинамики и переноса теплоты/влаги выполнено CFD-моделирование рабочей камеры с учетом уравнений Навье–Стокса, уравнения энергии и моделей турбулентности; граничные условия задавались по параметрам сушильного агента и характеристикам продукта. Исследовано влияние температуры и скорости воздуха, параметров вибрационного воздействия, толщины нарезки и начальной влажности на распределение скоростей, температур, интенсивность испарения и гидродинамическую устойчивость слоя. По результатам моделирования определены зоны неравномерного обдува и теплоподвода, а также предложены направления оптимизации геометрии воздухораспределения и режимов работы, обеспечивающие более равномерное поле температур и ускорение удаления влаги. Полученные данные могут быть использованы при проектировании и модернизации вибро-конвективных сушильных аппаратов для пищевого сырья с целью повышения энергоэффективности и качества готового продукта.

Ключевые слова: ANSYS Fluent, CFD-моделирование, вибро-конвективная сушка, чеснок, тепло- и массообмен, энергоэффективность, сушильная установка.

INTRODUCTION

Drying of garlic is a coupled heat–mass transfer process that includes heat supply to the material, moisture migration inside the product, and evaporation followed by removal of water vapor by the surrounding airflow. In convective systems, airflow structure, temperature distribution, and mass transfer are strongly interdependent, and the physicochemical properties of the food material significantly influence the drying behavior and final quality. Therefore, reliable simulation approaches are needed to support dryer design and to define energy-efficient operating regimes.

Drying kinetics of food products are often approximated using empirical or semi-empirical models. Although such models are convenient for fitting experimental curves, they usually do not explicitly account for airflow non-uniformity, permeability effects, local convective conditions, and scale-dependent flow features. CFD modeling provides spatially resolved velocity and temperature fields and enables physically consistent analysis of heat and mass transfer under real equipment geometry. In this work, ANSYS Fluent is used to model vibro-convective garlic drying and to justify constructive and regime improvements for an energy-saving vibro-convective unit.

MATERIALS AND METHODS

Materials and operating conditions

Garlic (Allium sativum L.) was considered in the form of slices with thickness $\delta = 2$ mm. The drying target was moisture reduction from $w_0 \approx 62\%$ to $w_f \approx 14\%$. The drying agent parameters were set to $T = 30$ °C and $v = 2$ m/s at the inlet. Vibration intensity was characterized by the peak acceleration $a = 60$ m/s², related to vibration frequency f and amplitude A by:

$$a = (2\pi f)^2 A$$

Table 1 summarizes the operating conditions used for CFD simulation [1, 2].

Table 1. Operating conditions and geometry (for CFD setup)

№	Item	Value

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1	Drying air temperature, *T*	30 °C
2	Inlet air velocity, *v*	2 m/s
3	Slice thickness, *δ*	2 mm
4	Initial moisture content, w_0	≈62%
5	Final moisture content, *w_f*	≈14%
6	Peak vibration acceleration, *a*	60 m/s²
7	Vibration relation	$a = (2\pi f)^2 A$
8	Chamber size (L×W×H)	[insert your real values]
9	Inlet size / position	[insert]
10	Outlet size / position	[insert]
11	Tray size / bed height	[insert]
12	Item	Value

Computational domain and boundary conditions

The CFD domain reproduces the vibro-convective dryer chamber with a dedicated inlet and outlet arrangement. The boundary conditions were defined as a velocity inlet (T = 30 °C, v = 2 m/s) and a pressure outlet (p = 0), while walls were treated as no-slip boundaries with an appropriate thermal condition (adiabatic or including heat loss, depending on the real unit). The garlic slices were located on the vibrating tray (δ = 2 mm), and moisture removal was represented through evaporation at the product surface (or equivalent source terms) [3-5].
Figure 1 presents the computational domain and the applied boundary conditions used in ANSYS Fluent.

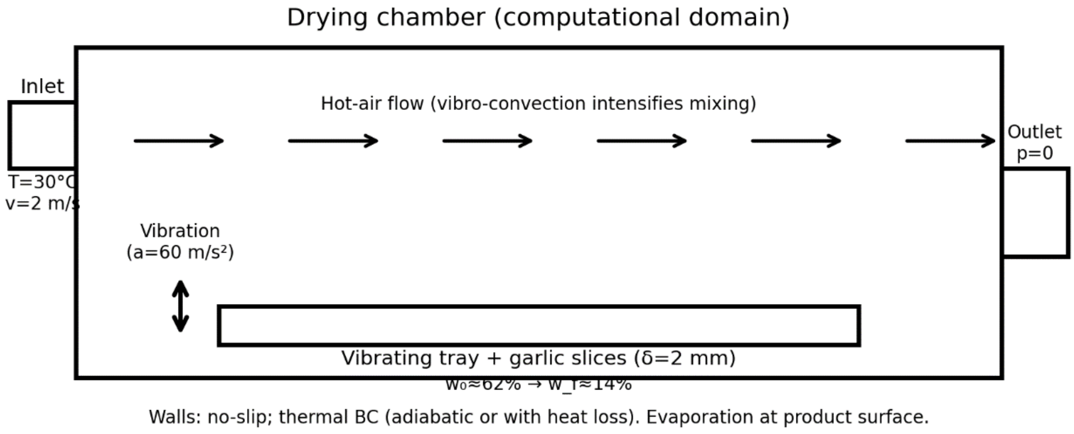

Figure 1. Computational domain and boundary conditions for vibro-convective garlic drying: inlet air (T = 30 °C, v = 2 m/s), outlet (p = 0), vibrating tray with garlic slices (δ = 2 mm), and peak vibration acceleration a = 60 m/s².

Governing equations and solver settings

Airflow was described by the conservation equations of mass, momentum (Navier–Stokes), and energy. Water vapor transport in the gas phase was considered via a scalar/species transport formulation coupled to evaporation at the product surface. A pressure-based solver with second-order discretization was used; turbulence was modeled with a robust RANS closure suitable for internal flows with possible recirculation [6-8].

RESULTS AND DISCUSSION

The CFD results provide spatially resolved velocity and temperature fields in the drying chamber and above the product layer. The analysis focuses on identifying non-uniform airflow supply, stagnant regions, and recirculation zones that can reduce convective transfer and cause non-uniform drying. Vibro-convection is expected to intensify mixing and reduce boundary-layer resistance in the near-tray region, which supports more uniform convective conditions.

Temperature field analysis demonstrates the quality of heat delivery to the garlic layer. Regions with higher local velocity generally show improved convective exchange, while low-velocity regions may produce delayed heating and reduced evaporation driving force. Compared to purely empirical drying kinetics, CFD modeling enables direct identification of geometric and regime-dependent causes of non-uniformity and provides a rational basis for improving air distribution and reducing energy losses [8-11].

CONCLUSION

ANSYS Fluent-based CFD modeling offers a physically grounded tool for analyzing vibro-convective garlic drying as a coupled airflow–heat–mass transfer process. Under the studied conditions ($T = 30$ °C, $v = 2$ m/s, $\delta = 2$ mm, $w_0 \approx 62\% \rightarrow w\_f \approx 14\%$, $a = 60$ m/s²), the model supports diagnosis of airflow/temperature non-uniformities and provides guidance for constructive and regime improvements of an energy-saving vibro-convective unit. The approach is suitable for modernization and scale-up, enabling better drying uniformity, improved product quality consistency, and reduced specific energy consumption [11-14].

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ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889, 2024-6.875 ResearchBib IF: 10.25 / 2025

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