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OPTIMIZATION OF A SOLAR AGRICULTURAL PRODUCT DRYER FOR NIGHTTIME OPERATION

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Abstract: *This paper details a numerical analysis of the thermal module with water-air heat exchanger for a continuous ultra-efficient, fully autonomous, net-zero emission agricultural dryer system. The research addresses the critical challenge of maintaining operational continuity during nighttime periods when direct solar radiation is unavailable, ensuring uninterrupted drying processes essential for agricultural product preservation. The study contributes to the global transition toward sustainable food processing technologies by developing a solar dryer capable of functioning independently of variable meteorological conditions, thereby supporting the European Green Deal objectives and renewable energy directive frameworks.*

Keywords: *Numerical simulation, optimization, heat exchanger, solar dryer*

1. Introduction

The 21st-century paradigm is fundamentally characterized by the acceleration of climate change and the imperative necessity of a global energy transition. In this context, the development of renewable energy conversion and storage technologies constitutes a fundamental pillar of sustainability strategies [1]. The IPCC Special Report on Global Warming of 1.5°C highlights the critical need to reduce CO2 emissions by 45% by 2030 compared to 2010 levels, aiming for climate neutrality by 2050 [2]. Within this complex and multidimensional framework, the agri-food sector faces unprecedented challenges, requiring innovative solutions that reconcile food security with decarbonization objectives. This strategic initiative aligns with the European Green Deal and Directive (EU) 2018/2001, which establishes a normative framework for increasing the share of renewables in the European Union's energy mix [3, 4].

Dehydration constitutes an essential thermal process in food processing, with significant implications for nutritional quality, shelf life, and the economic value of final products. According to the Food and Agriculture Organization (FAO), approximately 30-40% of agricultural products deteriorate before reaching consumers; implementing efficient dehydration technologies can substantially reduce these losses [5]. However, traditional drying processes are energy-intensive and carry a significant carbon footprint. Conventional dryers, predominantly powered by fossil fuels, emit an average of 2.5–3.0kg of CO_2 for every kilogram of water evaporated [6]. While solar drying offers a cleaner alternative, literature indicates that the global efficiency of such systems is often limited by intermittent radiation, although advanced thermal modules can improve performance by up to 35% [7].

The project "Ultra-efficient, totally autonomous, net-zero emissions continuous dryer" (UCES) provides a concrete response to these limitations by proposing a holistic integration of solar thermal and photovoltaic technologies. The fundamental innovation of the UCES system lies in its capacity to ensure continuous operation, independent of variable weather conditions, through a hybrid energy collection and storage architecture. The critical component of this architecture is the water-to-air heat exchanger module, which facilitates the efficient transfer of thermal energy stored in accumulation systems to the processed air within the drying chamber [8]. This module is the key element in overcoming the primary disadvantage of traditional solar systems: operational discontinuity during periods of insufficient solar radiation.

Recent studies emphasize the importance of maintaining process parameters within strict limits to ensure product quality; specifically, a minimum temperature of 50°C and relative humidity below 10% are critical values for preventing microorganism growth and undesirable enzymatic reactions [9]. Consequently, the research presented in this report focuses on optimizing the performance of heat exchangers under specific operating conditions, with a special emphasis on nocturnal regimes. By utilizing advanced numerical simulation methods, this study offers a profound understanding of heat transfer and fluid dynamic phenomena [10]. This approach allows for the design of a system that maximizes the energy density extracted from thermal storage while minimizing losses.

The socio-economic context of this research is particularly relevant for Romania and other member states with economies in transition. The Romanian agricultural sector, which contributes approximately 4.3% to the GDP and employs over 25% of the active population, faces major challenges regarding the modernization of processing capabilities [11]. The implementation of technologies developed within the UCES project can significantly contribute to increasing the competitiveness of local producers and reducing dependence on imported fuels. Therefore, this research is not merely an academic exercise in thermodynamic optimization but a substantial contribution to the energy transition of the agri-food sector [12]. The numerical simulation results presented provide the scientific foundations necessary for designing an industrial prototype capable of autonomous 24-hour operation, ensuring maximum energy efficiency and net-zero emissions throughout its life cycle.

2. Material and Method

Numerical simulation was implemented using Simcenter Amesim software, a specialized multidomain simulation platform capable of analyzing complex thermal and hydraulic processes. The simulation model presented in Fig. 1 contain a 200L solar collector reservoir with defined thermal capacity and convective heat loss coefficients to ambient conditions.

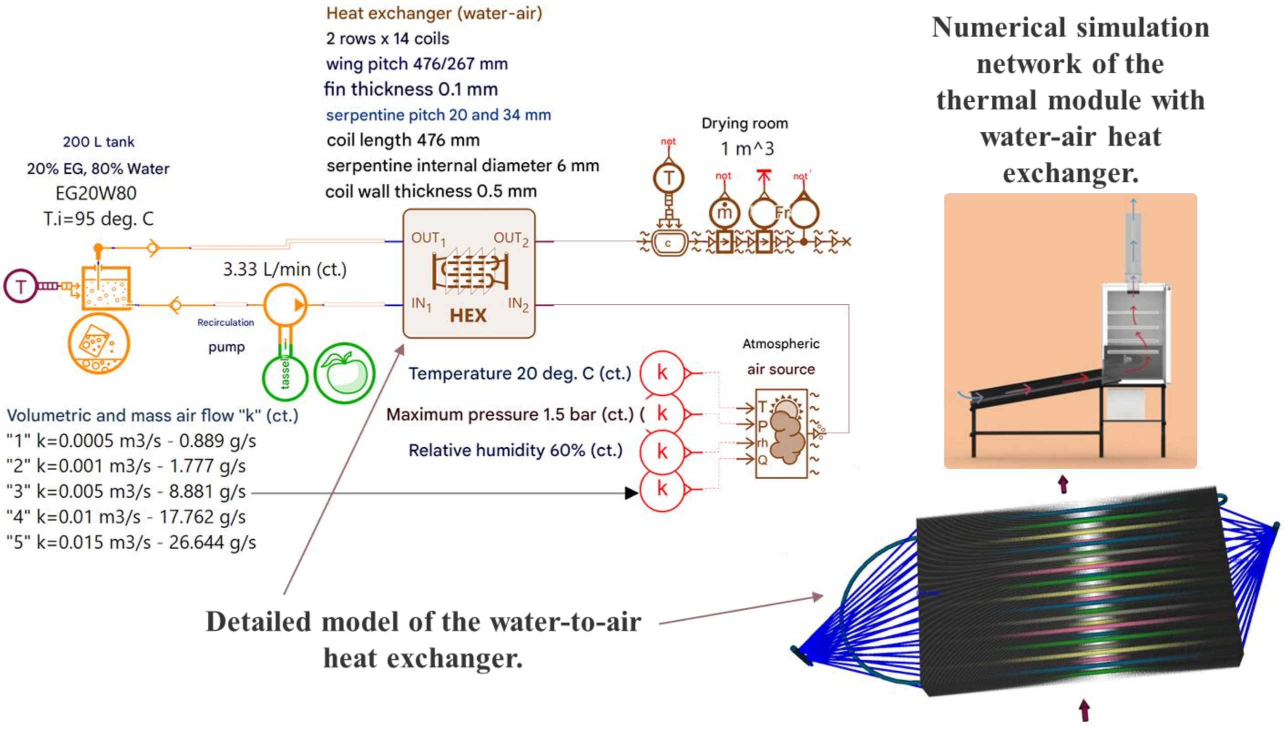

Fig. 1. Simulation network and physical model

The heat transfer fluid consisted of ethylene glycol 20% and water 80% mixture with a total volume of 204L and initial temperature of 95°C. The hydraulic network was dimensioned using DN25 pipes, with detailed modeling of linear head losses and pump energy consumption. The water-air heat exchanger was represented by a detailed 3D model featuring 28 serpentine tubes arranged in 2 rows with 6 mm internal diameter and 0.5 mm wall thickness. The atmospheric air source was modeled with constant mass flow rates ranging from 0.0005 to 0.015m^3/s, at 20°C with 60% relative humidity. The drying chamber was represented as a controlled 1m^3 volume where complex thermodynamic processes including evaporation, condensation, and humidity dynamics were simulated.

The parametric simulation was structured as a systematic experimental protocol consisting of 5 simulation runs, with the volumetric air flow rate serving as the independent variable. The boundary conditions were established to simulate nighttime operational conditions, where the sole thermal energy source was the heat stored in the solar collector reservoir. The initial conditions were defined with the heat transfer fluid at 95°C, the drying chamber environment at 20°C ambient temperature, and 60% initial relative humidity. The performance evaluation was based on 5 critical optimization criteria: the heat exchanger efficiency must exceed 90%; the final temperature within the drying chamber must reach or exceed 50°C; the relative humidity must be maintained at or below 10%; the air flow rate must be sufficiently low to prevent displacement of agricultural products within the chamber; and the continuous operation duration must cover the entire 10 hour nighttime period. This comprehensive evaluation framework ensured the identification of optimal operating parameters that simultaneously satisfy technical, product quality, and operational requirements.

3. Results and Discussion

The temperature of the heat transfer fluid within the reservoir and the temperature within the drying chamber (presented in Fig. 2.) demonstrate a complex relationship with the air flow rate.

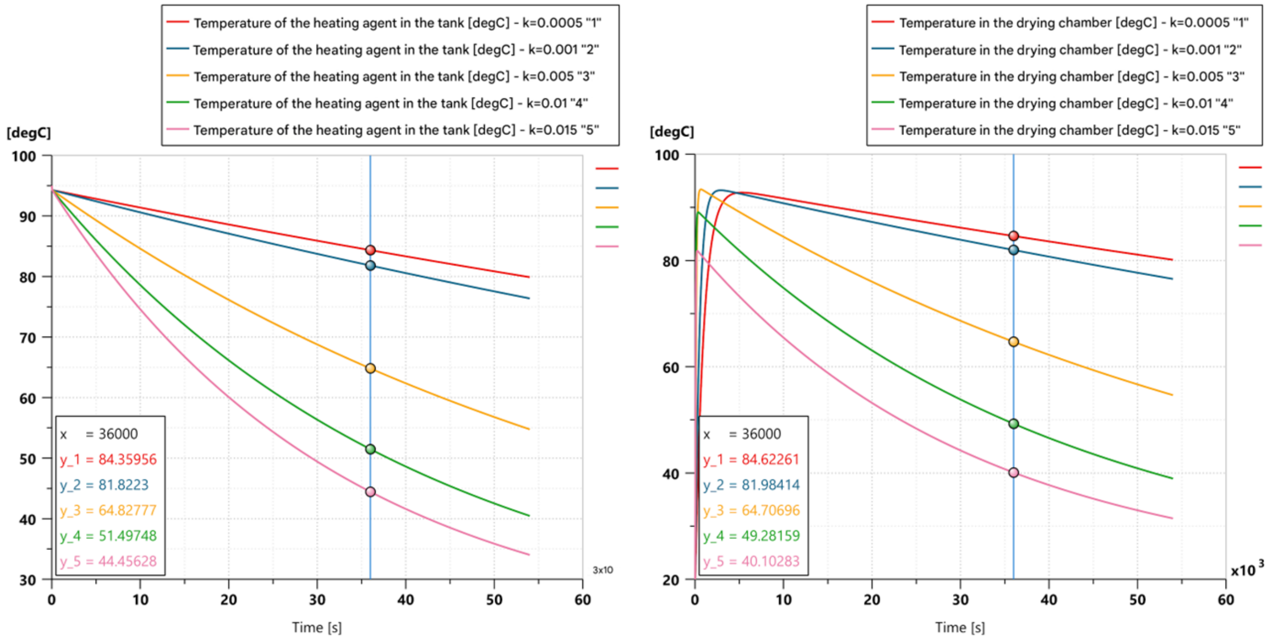

Fig. 2. Dynamic evolution of temperatures

The reservoir temperature figure shows a progressive decline from the initial 95°C over the 10 hours simulation period, with the highest air flow rate producing the most rapid temperature decrease to 44.45°C at 10 hours, while the lowest air flow rate maintains a significantly higher temperature of 84.36°C. The drying chamber temperature figure reveals that all air flow rates except the highest successfully maintain temperatures above the critical 50°C threshold, with the lowest air flow rate achieving 84.62°C after ten hours, while the highest flow rate drops to 40.1°C.

The air flow rate of 0.01 m3/s represents an optimal compromise, maintaining the drying chamber temperature at 49.28°C after 10 hours of operation. These thermal profiles confirm the direct correlation between air flow rate and thermal energy extraction rate, with significant implications for the operational duration and product quality.

Fig. 3. show the dynamic evolutions of heat flux through the heat exchanger and the thermal efficiency of the heat transfer process, these provide critical insights into the system's energy conversion performance. The heat flux figure demonstrates that the maximum heat transfer rate occurs at the beginning of the process and progressively declines as the heat transfer fluid cools, with the highest air flow rate achieving a maximum heat flux of 540W, while the lowest air flow rate maintains a minimum heat flux of 58W. This confirms the direct relationship between air flow rate and thermal energy transfer intensity. The thermal efficiency figure reveals that all air flow rates maintain efficiency within a relatively narrow range of 0.82 to 0.99, with the lowest flow rates achieving values closest to the maximum. Notably, the highest air flow rate produces an efficiency of 0.82, which falls below the required 90 percent threshold, while all other flow rates exceed this critical performance benchmark. The graph confirms that the value of the convection coefficient is between 321 and 341 W/m²/K. At higher air flows, an increased variability of the coefficient is observed. This instability is a consequence of the heat transfer relationships, being correlated with the temperature differences between the supply and return flows, which become more significant at high flow rates.

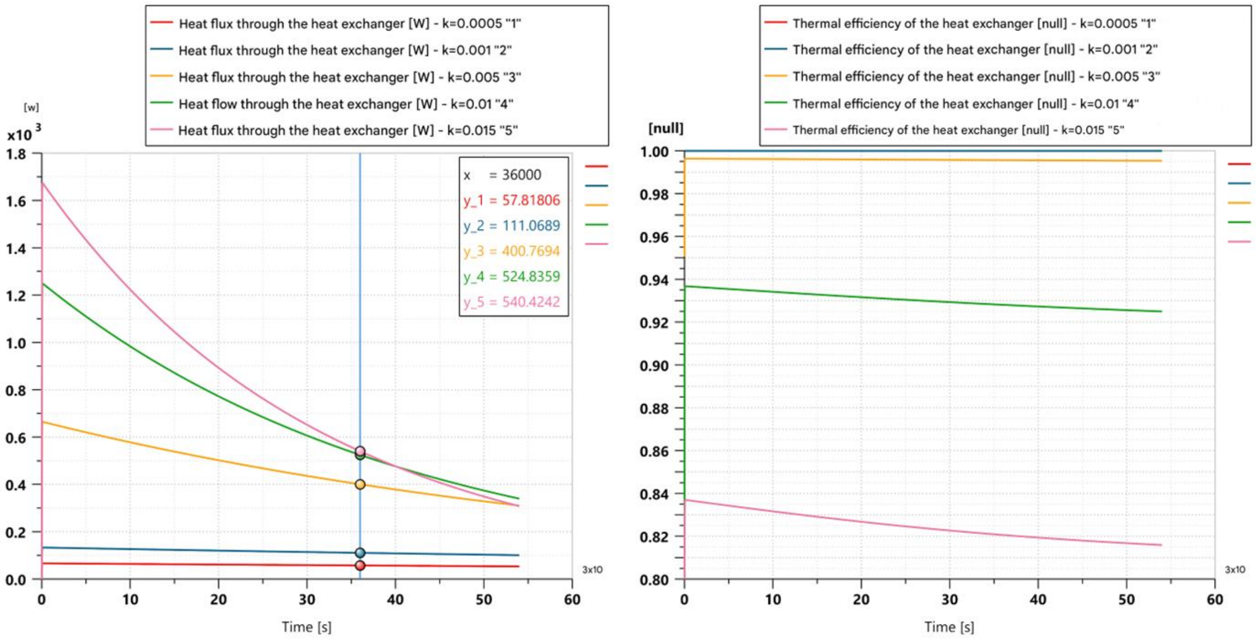

Fig. 3. Heat transfer characteristics

Fig. 4. show the dynamic evolutions of the relative humidity within the drying chamber and the cumulative energy transferred to the drying chamber, these demonstrate the system's effectiveness in achieving optimal drying conditions. The relative humidity figure shows a rapid initial decrease in relative humidity during the first hour of operation, followed by stabilization for most air flow rates, with the exception of the two highest flow rates. The highest air flow rate initially reduces humidity most rapidly but experiences humidity increases after 10 hours due to temperature decline, while the remaining flow rates maintain relative humidity below the critical 10% threshold throughout the entire operational period. The cumulative energy figure demonstrates a direct relationship between air flow rate and total energy transferred, with the highest flow rate transferring 39.9MJ of energy compared to 8.5MJ for the lowest flow rate at 36000 seconds. This behavior aligns with fundamental heat transfer principles where increased

mass flow rate of the cold fluid enhances thermal energy transfer. However, this energetic advantage results in accelerated consumption of stored thermal energy, thereby limiting the system's operational duration.

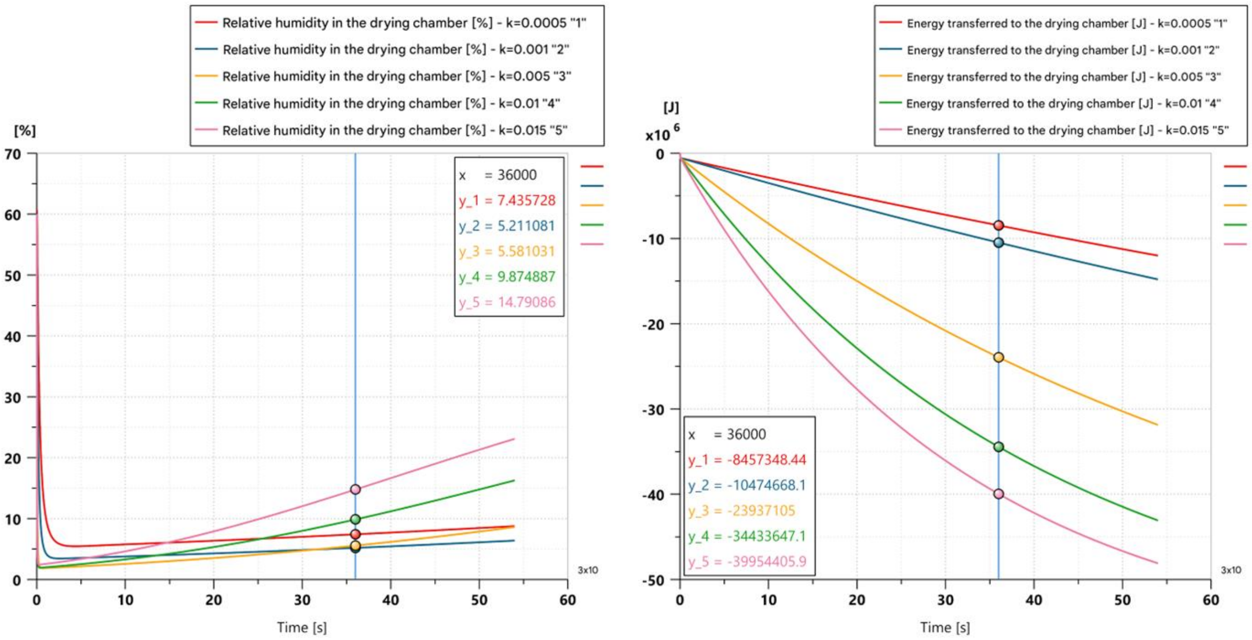

Fig. 4. Humidity control and energy transfer dynamics

Fig. 5 confirms that the air mass flow rate is maintained constant for each simulation run, as prescribed by the experimental protocol.

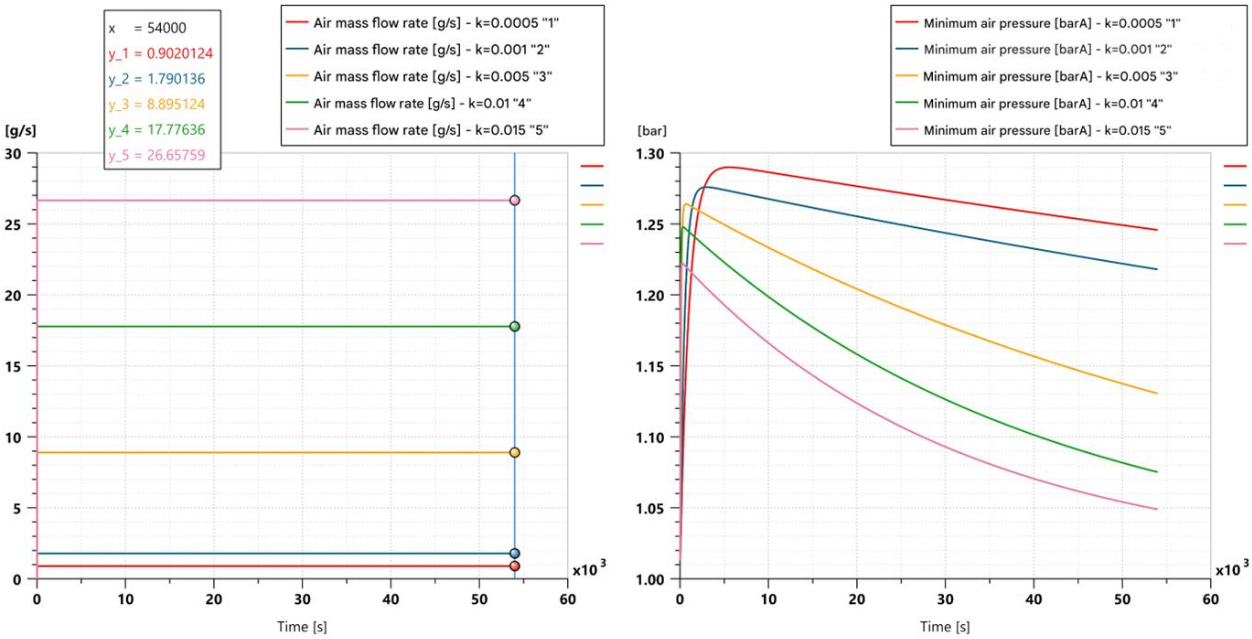

Fig. 5. Evolution of pneumatic parameters

The values are ranging from 0.9 g/s for the lowest volumetric flow rate to 26.6 g/s for the highest flow rate. The pump discharge pressure curves demonstrate minimal variation over time, with all curves remaining within a very narrow range of 1.0195 to 1.02 bar, indicating minimal head losses in the hydraulic network and confirming the hydraulic design efficiency. The minimum air pressure figure reveals a distinct dynamic behavior, showing an initial pressure increase at system startup followed by gradual decline due to air heating and expansion, with higher air flow rates experiencing more pronounced pressure decreases, suggesting important considerations for fan selection and system design. The hydraulic characteristics of the system reveal important insights regarding flow stability and pressure dynamics. The mass flow rate of the heat transfer fluid figure shows that the mass flow rate remains approximately constant over time for all five simulated cases, with slight increases observed throughout the simulation period due to temperature variations.

The dynamic evolution of the convection coefficient and associated heat losses presented in Fig. 6 reveals critical thermodynamic behavior that warrants deeper theoretical consideration. The observed convection coefficient range (321-341 W/m²/K) aligns with established correlations for forced convection in serpentine tube configurations, though the noted instability at higher flow rates suggests transitional flow regime characteristics that merit further investigation through dimensionless analysis. The inverse relationship between airflow rate and heat loss magnitude, while consistent with Fourier's law of heat conduction, demonstrates a non-linear response that challenges conventional lumped parameter modeling approaches.

The observed thermal loss dynamics reflect complex interactions between the system's thermal inertia and the time-dependent boundary conditions. The minimal heat loss at elevated flow rates, despite the increased convective heat transfer surface activity, indicates a dominant influence of the temperature potential gradient as the primary driver of parasitic heat losses. This phenomenon suggests that conventional thermal insulation strategies may require re-evaluation when applied to systems with dynamic operational profiles.

From a system optimization perspective, the heat loss profile reveals a critical trade-off between thermal storage utilization efficiency and energy conservation.

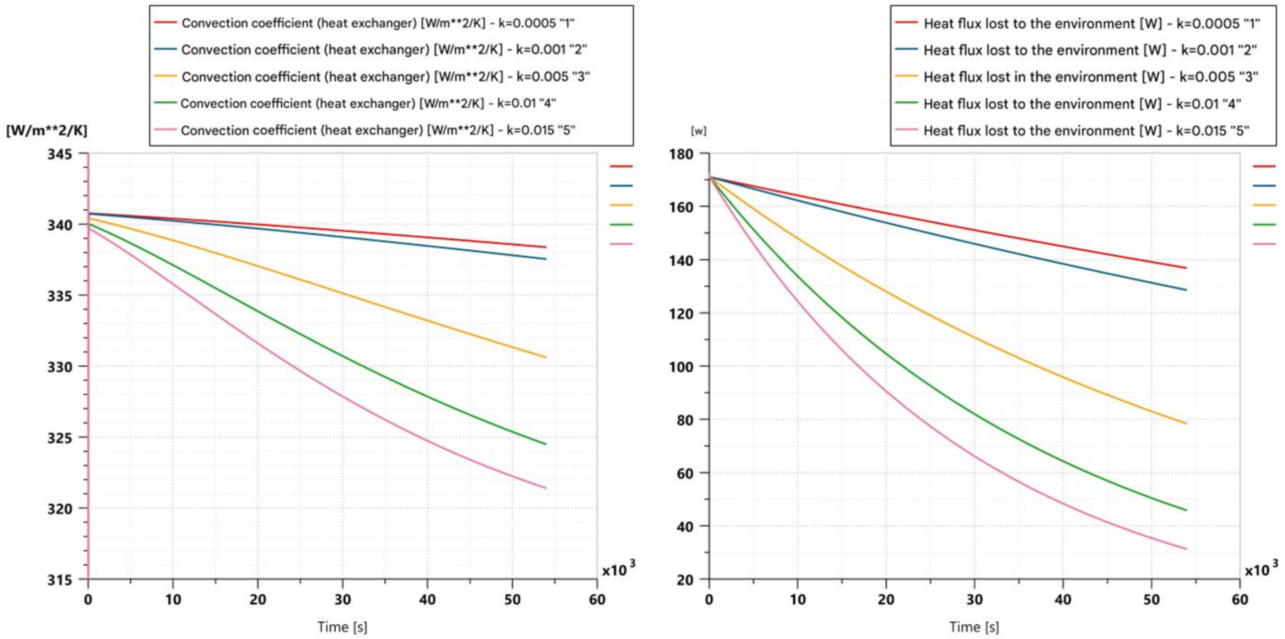

Fig. 6. Evolution of convection coefficient and heat losses

Prolonged exposure of thermal tank at high temperatures and at lower flow rates creates a significant energy loss, which cannot be fully compensated by the reduced convective losses during operational transitions. This observation has profound implications for the design of thermal storage systems in intermittent renewable energy applications.

The temporal evolution of the convection coefficient provides valuable information about the transient thermal behavior of the system, which could inform more sophisticated control algorithms. The stability of the coefficient at lower flow rates, in contrast to the increased variability at higher flow conditions, suggests potential opportunities for adaptive control strategies that could optimize the thermal extraction process while minimizing parasitic losses.

These observations highlight the need to consider second-law thermodynamics in the design of thermal energy storage systems for agricultural processing applications. The observed heat loss patterns indicate that conventional first-law efficiency values may be insufficient to capture the actual thermodynamic performance of such systems, especially during extended nighttime operation when the system operates solely on stored thermal energy.

4. Conclusions

Numerical simulation of the thermal module with water-air heat exchanger has successfully identified the optimal air flow rate for nighttime operation of the net-zero emission continuous dryer system.

The comparative analysis of 5 operational scenarios demonstrated that an air flow rate of 0.01m^3/s represents the ideal balance between sufficient thermal energy extraction from the storage system and maintenance of process parameters within critical limits for agricultural product drying. At this optimal flow rate, the drying chamber temperature remained at 49.28°C after 10 hours of operation, the relative humidity was consistently maintained below 10%, and the heat exchanger efficiency exceeded the 90% threshold throughout the entire process duration.

These results confirm the technical feasibility of continuous nighttime operation for solar drying systems through the integration of thermal storage and optimized heat exchange processes.

This research provides a scientific foundation for the design and implementation of net-zero emission agricultural drying technologies that align with European Green Deal objectives and renewable energy directives, offering a practical solution for reducing the carbon footprint of the agricultural processing sector while enhancing food security through effective post-harvest preservation.

The optimized thermal module design represents a significant advancement toward sustainable food processing systems with full operational autonomy regardless of meteorological conditions.

Acknowledgment

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