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Comparison of Airflow Velocity Distribution at the Inlet in Single and Dual Inlet Cabinet Dryer: A CFD Study

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Abstract: This study explores how airflow velocity is distributed in cabinet dryers with single and dual inlet systems, using Computational Fluid Dynamics (CFD) simulations. The goal was to compare how different inlet configurations affect airflow uniformity and drying performance across various rack levels. We tested four dual inlet setups with varying mass flow ratios (50%/50%, 40%/60%, 30%/70%, and 20%/80%) and compared them to a single inlet system. The results show that the single inlet configuration creates uneven airflow, with higher velocities at the top racks and lower velocities at the bottom, leading to inconsistent drying. On the other hand, dual inlet systems provide more even airflow, with the 50%/50% configuration being the most balanced. Even the more uneven dual inlet setups (such as the 20%/80% ratio) still performed better than the single inlet in terms of airflow consistency and drying efficiency. Overall, dual inlet systems, especially those with balanced airflow, enhance drying efficiency by ensuring more uniform airflow throughout the dryer. Further research could focus on optimizing these dual inlet systems for even better performance.

Keywords: Airflow velocity distribution, Cabinet dryer, Computational fluid dynamics (CFD)

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1. Introduction

Cabinet dryers are extensively used in the food and pharmaceutical industries, particularly in processes that involve drying through heated air circulation [1]. The distribution of airflow within the drying chamber is a critical factor that determines both the efficiency of the process and the quality of the final product [2]. Non-uniform airflow can result in uneven drying, leading to less optimal product outcomes and increased energy usage [3]. Therefore, understanding how airflow is distributed within cabinet dryers is essential for enhancing design and improving system performance.

Traditionally, cabinet dryers use a single inlet to introduce hot air into the chamber. However, the dual inlet system presents a potentially more efficient alternative, offering the benefit of providing a more uniform airflow distribution across the drying chamber [4]. This system allows for better control of the airflow by dividing it into two separate channels, with the mass flow rates at each inlet adjustable [5]. Altering the mass flow rates at each inlet can significantly affect the airflow velocity inside the dryer, thus possibly improving drying efficiency [6].

Previous research has examined the use of dual inlet systems across various engineering fields, such as ventilation and power generation [7][8]. In drying applications, some studies have suggested that adding a second inlet can improve airflow uniformity and reduce the formation of low-velocity zones, which could otherwise lead to irregular drying [9][10]. However, while dual inlets show promise, there remains a lack of understanding of how to optimize airflow distribution with varying mass flow rates at each inlet [11][12].

To address this gap, Computational Fluid Dynamics (CFD) has become a valuable tool for modeling and analyzing airflow in drying systems [13]. CFD enables precise simulations of fluid flow, allowing for the visualization of velocity distributions and the evaluation of how different design parameters and operational conditions affect system performance [14]. Though CFD has been applied to study airflow in cabinet dryers, limited research has been dedicated to comparing single and dual inlet systems with varying airflow mass ratios [15][16].

This study aims to fill this gap by comparing the airflow velocity distribution in cabinet dryers with one and two inlets using CFD simulations. The dual inlet system is tested under four different mass flow distribution configurations: 50%/50%, 40%/60%, 30%/70%, and 20%/80% [17]. By analyzing these variations, we seek to understand how different inlet flow ratios influence the velocity profile within the drying chamber. The insights gained from this research will contribute to optimizing inlet design for better drying performance, particularly by achieving a more even airflow distribution.

Earlier studies on airflow in drying chambers have demonstrated that uneven airflow near the inlet can lead to increased drying time and higher energy consumption [18]. Through CFD simulations, this study investigates how different mass flow distribution ratios affect the airflow velocity inside the chamber and determines which configuration provides the most uniform airflow [19]. Furthermore, it compares the performance of single and dual inlet systems under similar conditions, offering a comprehensive view of the benefits and drawbacks of each design.

While literature on dual inlet systems in drying processes exists, much of the research has focused more on theoretical airflow behavior rather than practical comparisons between various inlet configurations with different mass flow distributions [20]. This research seeks to address this by offering a practical comparison of multiple inlet configurations, relevant for industrial-scale cabinet dryer design [21].

By contributing to the understanding of inlet system design, this study offers practical insights for selecting the most appropriate configuration to enhance drying efficiency. The results will not only support the development of drying technology but also provide a foundation for further investigations into optimizing airflow in different drying systems [22].

2. Materials and Methods

2.1. Experimental Setup

This study utilized Computational Fluid Dynamics (CFD) simulations to analyze the airflow velocity distribution in cabinet dryers with both single and dual inlets. The two configurations were modeled with identical dimensions, with the only difference being the number of inlets. The cabinet dryer was represented in a two-dimensional geometry with the following dimensions: height of 1000 mm and width of 650 mm. These dimensions reflect a typical industrial dryer used in food and pharmaceutical processing. The simulation was set up to accurately model airflow behavior within the drying chamber. The design of the cabinet dryer is shown in Figure 1.

2.2. Model Creation and Mesh Generation

The two-dimensional model of the cabinet dryer was created based on the given dimensions, ensuring the geometry mirrored a real-world industrial dryer system. The model was developed using ANSYS Fluent, a widely used CFD software, which enabled precise airflow analysis. The geometry was subdivided into small control volumes, or cells, to solve the fluid flow equations numerically.

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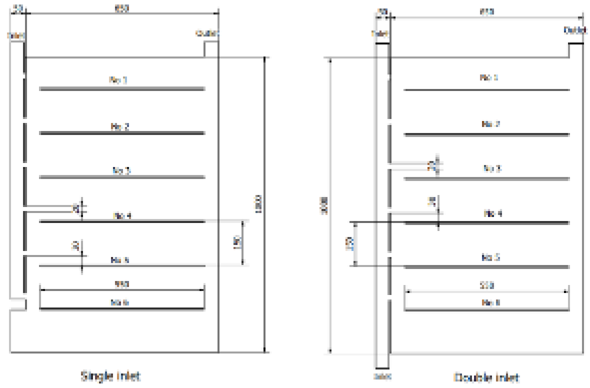

Figure 1. Single and double drying chamber design

A mesh size of 5 mm was used to strike a balance between computational efficiency and the accuracy of the results. A finer mesh was applied near critical areas such as the inlets and the region where airflow changes were most significant. Mesh independence tests were conducted to confirm that the results were not influenced by mesh resolution. The final mesh consisted of approximately 1.5 million cells, ensuring adequate resolution for capturing detailed airflow patterns.

2.3 Boundary Conditions

The boundary conditions were set to simulate the operational characteristics of the drying system. For the single inlet configuration, a constant mass flow rate of 0.01 kg/s was applied at the inlet. For the dual inlet configuration, the mass flow rate was split between the two inlets based on varying ratios: 50%/50%, 40%/60%, 30%/70%, and 20%/80%. For example, in the 50%/50% configuration, each inlet received 0.005 kg/s, while in the 40%/60% configuration, inlet 1 received 0.004 kg/s, and inlet 2 received 0.006 kg/s. The outlet boundary condition was set as a pressure outlet with atmospheric pressure to allow free flow of air from the dryer. This setup ensured that the primary focus was on evaluating how different inlet configurations impacted the airflow distribution.

Velocity measurements were taken at specific locations along the inlet plane of the drying chamber. These points corresponded to the openings of the inlets on each rack inside the dryer. These locations were chosen to measure the velocity directly at the inlet points, capturing the airflow distribution as the air entered the drying chamber. The airflow characteristics were analyzed along this plane to assess how variations in inlet mass flow and configurations influenced the velocity profiles within the dryer.

2.4 Simulation Parameters

The air was modeled as an incompressible fluid with constant properties, and the simulations were run under steady-state conditions. The simulations were designed to observe how the airflow velocity varied based on the inlet configurations. Each scenario was analyzed to ensure the airflow velocity at the inlets was stabilized before the results were used for analysis. The study included a comparison between the single inlet and the four dual inlet configurations with varying mass flow ratios.

2.5 Data Collection and Analysis

After the simulations were completed, the airflow velocity data were extracted at the designated measurement points, specifically at the inlet openings on each rack. The primary metrics for analysis were the velocity magnitudes at these points and the uniformity of the airflow distribution across the entire dryer chamber. These velocity profiles were compared across different configurations to determine the most effective inlet setup for achieving uniform airflow and efficient drying.

By analyzing the data from the simulations, this study aimed to identify which inlet configuration resulted in the most evenly distributed airflow. The impact of different mass flow rates and inlet configurations on the airflow performance was thoroughly evaluated, with the goal of optimizing dryer efficiency.

3. Results

3.1 Single Inlet Configuration

In the case of the single inlet configuration (Figure 2), the airflow is highly concentrated at the top rack (rack No. 1), resulting in uneven distribution of air throughout the enclosure. This concentration may lead to overheating in the lower racks due to insufficient ventilation, which can compromise the overall thermal management efficiency of the system. Such airflow patterns highlight the limitations of the single inlet design in maintaining consistent cooling performance across all rack levels.

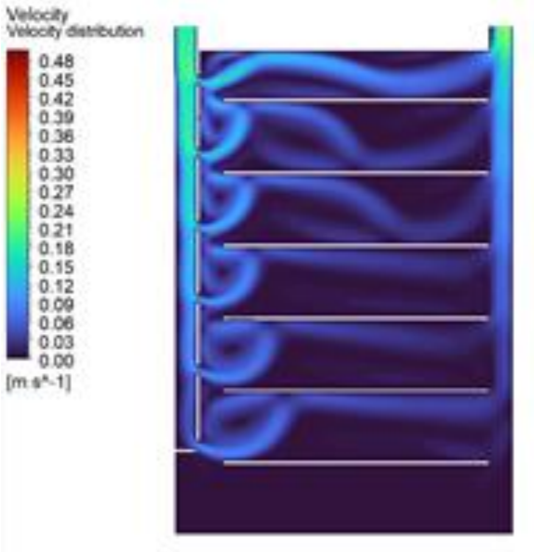

Figure 2. Single inlet velocity distribution.

3.2 Dual Inlet Configuration

When we shift to dual inlet configurations (Figure 3), the airflow is split between two inlets, allowing for a more uniform distribution across the drying chamber. This setup significantly improves ventilation efficiency by reducing airflow concentration in a single region, as observed in the single inlet configuration. Moreover, the differences in airflow velocities between the two inlets—arising from varying mass flow distributions—are evident, indicating the influence of inlet placement and flow rate balance on the overall airflow pattern. Such configuration enhances the potential for consistent drying performance across all rack levels.

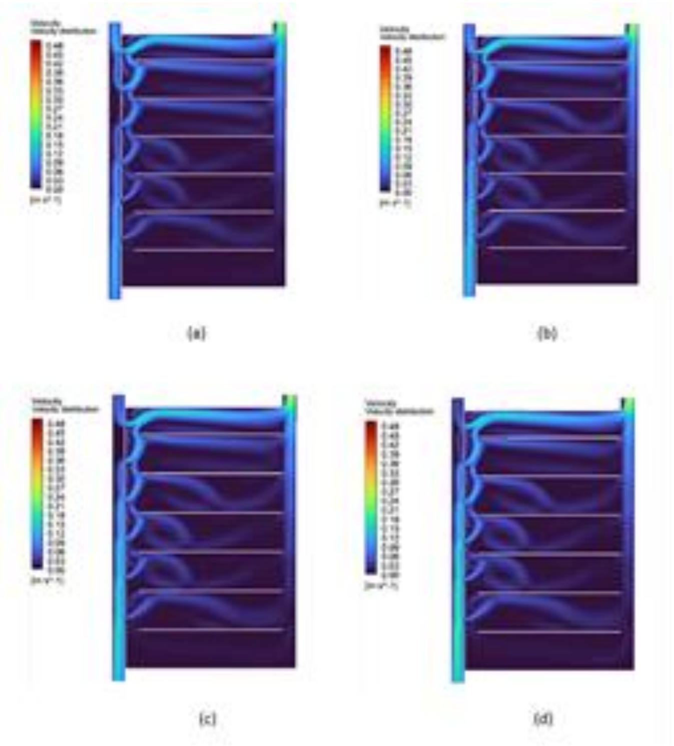

Figure 3. Double inlet velocity distribution: (a) inlet fraction 50%/50%; (b) inlet fraction 40%/60%; (c) inlet fraction 30%/70% ; (d) inlet fraction 20%/80%.

3.3 Graphical Analysis of CFD Simulation Results

The graph (Figure 4) presents a comparative analysis of airflow velocities across different rack levels for both the single inlet and dual inlet configurations. For the dual inlet setup, four distinct mass flow distribution scenarios are examined: 50%/50%, 40%/60%, 30%/70%, and 20%/80%. The data clearly illustrate how varying the proportion of inlet mass flow affects the vertical airflow distribution within the chamber. In contrast to the single inlet configuration—where airflow is predominantly concentrated at the top—the dual inlet setups demonstrate a more balanced velocity profile, particularly under more evenly split flow conditions. These findings highlight the importance of inlet configuration and flow distribution in optimizing airflow performance across all levels of the drying chamber.

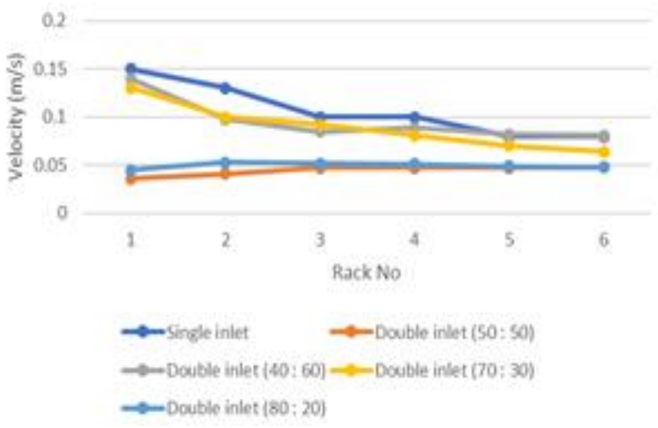

Figure 4. Velocity value on each rack inlet

4. Discussion

Figure 2 shows velocity profile of single inlet cabinet reveals a significant drop in airflow speed as it progresses deeper into the chamber. Specifically, the airflow near the top racks is much higher than at the bottom, creating an uneven distribution of airflow. At rack 1, the topmost rack, airflow velocity is at its peak, while at rack 5 (the bottom), the velocity decreases substantially. This uneven airflow distribution implies that drying rates are faster at the upper levels, with the lower levels suffering from slower drying. This scenario could lead to inconsistencies in drying efficiency across the chamber, as materials on higher racks might dry more quickly than those on lower racks, where airflow is significantly weaker. The single inlet configuration thus results in a less uniform drying profile, which can hinder overall drying efficiency, especially when consistent moisture removal is crucial. To address this, additional measures such as air circulation enhancement could be explored.

In the Figure 3, the airflow of 50%/50% dual inlet configuration, is evenly distributed between the two inlets. As a result, the airflow velocity across the chamber shows a more uniform pattern. Compared to the single inlet configuration, this setup reduces the sharp variations in airflow velocity across different rack levels. Both the top and bottom racks receive relatively similar airflow velocities, leading to more consistent drying conditions across all levels. This balanced distribution of airflow makes the 50%/50% configuration ideal for applications where uniform drying is desired. It ensures that drying efficiency is optimized and that moisture removal is more consistent throughout the chamber.

As the mass flow rate between the two inlets becomes increasingly imbalanced in configurations such as 40%/60%, 30%/70%, and 20%/80%, the velocity profiles show more pronounced differences. The racks nearer to the stronger inlet (inlet 2) experience higher airflow velocities, while the racks closer to the weaker inlet (inlet 1) receive reduced airflow. In the 40%/60% configuration, there is a noticeable distinction in airflow velocities between the two inlets. The top racks closer to inlet 2 benefit from higher airflow, while inlet 1's lower mass flow results in less airflow at the bottom racks. Although this configuration improves airflow distribution compared to the single inlet system, some imbalances remain, particularly at the lower racks, where airflow is weaker. The 30%/70% configuration further emphasizes this imbalance. Here, rack 1 and the upper levels receive significantly higher velocities due to the dominance of inlet 2, which supplies 70% of the airflow. Meanwhile, racks close to inlet 1 receive less airflow, which causes a noticeable variation in velocity profiles across the drying chamber. As a result, this configuration still enhances airflow distribution but is not as uniform as the 50%/50% setup. The 20%/80% configuration shows the most extreme imbalance. With inlet 2 receiving 80% of the airflow, the racks closer to this inlet experience much higher velocities, while airflow near inlet 1 is minimal. Consequently, racks near inlet 1 face slower drying due to reduced airflow, whereas racks near inlet 2 benefit from much stronger airflow. This setup creates the least uniform drying profile, with significant differences in drying rates between the top and bottom racks.

The graph in Figure 4 clearly shows that rack 1 experiences the highest airflow velocities, the single inlet configuration, which sharply decline as we move towards the bottom racks. This uneven airflow distribution leads to faster drying at the top and slower drying at the bottom, highlighting the limitations of the single inlet system in providing uniform drying conditions. The 50%/50% dual inlet configuration offers a more balanced velocity distribution, with relatively consistent airflow velocities across the racks. The graph illustrates that this configuration reduces the steep drop in velocity observed in the single inlet system, ensuring more even drying conditions throughout the drying chamber. As the mass flow distribution becomes increasingly imbalanced (40%/60%, 30%/70%, 20%/80%), the graph shows higher velocities near inlet 2 and lower velocities near inlet 1. The 20%/80% configuration displays the most uneven airflow distribution, where the velocity drop-off between the top and bottom racks becomes significantly more pronounced compared to the more balanced configurations here.

5. Conclusions

This study examined how airflow velocity varies in cabinet dryers with single and dual inlet configurations, using CFD simulations. The results showed that the single inlet system caused significant differences in airflow, with high velocities at the top racks and much lower velocities at the bottom, resulting in uneven drying across the chamber. In comparison, the dual inlet systems provided a more consistent airflow. The 50%/50% dual inlet configuration was the most effective, offering uniform airflow throughout the dryer. Even when the mass flow rates were uneven, as in the 40%/60%, 30%/70%, and 20%/80% configurations, the dual inlet systems still performed better than the single inlet design, with more consistent airflow and better drying performance. The 20%/80% configuration, though highly imbalanced, still achieved more consistent airflow than the single inlet system. Overall, dual inlet systems, particularly those with more balanced airflow, significantly enhance drying efficiency and provide more even drying conditions.

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