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Computational Fluid Dynamics (CFD) Analysis of a Solar Dryer with Backup Incinerator

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Abstract

Experimental investigations have been conducted to improve agricultural products' drying rate through solar dryers. Computational Fluid Dynamics (CFD) has emerged as a powerful tool for optimizing design. Drying in enclosed spaces with vents has been employed to mitigate the challenges associated with open sun drying, including contamination by dirt, pests, and rodents. This study focuses on the design and experimental evaluation of a solar dryer with a backup incinerator for drying selected farm produce. The dryer's performance was also modeled and simulated using CFD to analyze temperature distribution under varying wind velocities. A 3D model of the solar flat plate collector was developed using ANSYS Workbench (3D, pressure-based, standard k-epsilon), and meshing was created in ANSYS ICEM, consisting of 95,715 nodes and 522,760 elements. Results from ANSYS FLUENT revealed that the temperature during solar drying is directly proportional to solar radiation, with a maximum collector temperature of 76°C at the absorber plate and 59°C on the drying trays at an air velocity of 3.5 m/s. Experimental validation showed CFD results to be higher due to material property variations. During incinerator-assisted drying, a uniform temperature of 45°C was observed with forced convection. This setup is viable for crop drying during cloudy weather and at night.

Keywords: Computational Fluid Dynamics, Solar dryer, Backup, Incinerator

1. Introduction

Solar dryers harness solar energy to enhance drying while safeguarding agricultural produce from pests, dirt, and rain [1-3]. Compared to open sun drying, solar dryers offer higher temperatures, reduced relative humidity, lower moisture content, and minimized spoilage [4-5]. Solar dryers are categorized into direct, indirect, and specialized types [6-7]. Direct dryers expose the produce to solar radiation through a transparent cover, while indirect dryers use a solar collector to heat air, which is then circulated to dry the produce. Specialized dryers, often hybrid systems, combine solar energy with other energy sources for specific products [8-9].

Moisture transfer occurs as water vaporizes from the product surface into circulating air. Heat and moisture transfer rates depend on the temperature and velocity of the drying air [10]. Physical experimentation for design optimization is time-consuming and costly, whereas CFD allows for rapid, cost-effective testing of designs [11]. Studies by Kumavat [12] and Kumar et al. [13] demonstrated that CFD is an effective tool for simulating solar drying processes under various conditions.
This study employs CFD to model and analyze

a solar dryer with a backup incinerator, focusing on temperature distribution under varying wind velocities using experimental values.

2. Computational Fluid Dynamics (CFD)

Solar dryers are a sustainable and effective solution for preserving agricultural produce, utilizing solar energy to enhance drying processes while simultaneously safeguarding the produce from pests, dirt, and rain [2]. Traditional open sun drying, though widely practiced, exposes produce to several risks, including contamination, spoilage, and inconsistent drying. Solar dryers address these challenges and offer numerous advantages, such as higher drying temperatures, reduced relative humidity, lower residual moisture content, and minimized spoilage [4]. These benefits make solar dryers an indispensable technology for enhancing food security and reducing post-harvest losses, especially in regions with abundant solar radiation.

2.1 Types of Solar Dryers

Solar dryers can be broadly classified into three categories: direct, indirect, and specialized dryers [5]. Each type serves unique purposes and is suited to specific agricultural products and climatic conditions.

1. **Direct Solar Dryers:** Direct solar dryers are the simplest type, where the produce is directly exposed to solar radiation through a transparent cover. The transparent material, often glass or plastic, allows sunlight to pass through and trap heat inside the drying chamber. This setup creates a greenhouse effect, elevating the internal temperature and enhancing the drying process. Direct dryers are particularly effective for drying robust products like grains, nuts, and certain fruits that are less sensitive to prolonged exposure to sunlight. However, this method has limitations, such as the risk of discoloration or nutrient degradation in light-sensitive produce.

2. **Indirect Solar Dryers:** Indirect solar dryers address some of the limitations of direct dryers by using a solar collector to heat the air, which is then circulated through the drying chamber. In this design, the agricultural produce is not exposed to direct sunlight, preventing discoloration and preserving sensitive nutrients. The heated air absorbs moisture from the produce and exits through vents, ensuring a continuous drying process. Indirect dryers are ideal for products like medicinal plants, spices, and leafy vegetables, where preserving quality and color is paramount.

3. **Specialized Solar Dryers:** Specialized solar dryers, often hybrid systems, combine solar energy with additional energy sources such as biomass, electricity, or gas to ensure consistent drying performance. These systems are particularly useful in regions with variable solar intensity or during adverse weather conditions. For instance, hybrid solar dryers can utilize biomass as a backup energy source during cloudy days, ensuring uninterrupted drying. Specialized dryers are also designed for specific applications, such as drying high-value crops or industrial products, and often include advanced features like automated controls and humidity sensors [6].

2.2 Principles of Moisture and Heat Transfer in Solar Dryers

The drying process in solar dryers relies on the principles of moisture and heat transfer. Moisture transfer occurs as water vaporizes from the surface of the product and is carried away by the circulating air. Heat transfer, on the other hand, involves the transfer of thermal energy from the heated air to the product, raising its temperature and accelerating moisture evaporation. The rates of heat and moisture transfer are influenced by several factors, including the temperature, humidity, and velocity of the drying air [7]. Higher air temperatures increase the vapor pressure difference between the product and the surrounding air, enhancing the drying rate. Similarly, higher air velocity reduces the boundary layer resistance around the product, facilitating efficient moisture removal.

2.3 Limitations of Physical Experimentation in Solar Dryer Design

Traditionally, the design and optimization of solar dryers have relied on physical experimentation. While effective, this approach has significant limitations. Experimentation is often time-consuming and resource-intensive, requiring extensive trials to evaluate various design parameters and environmental conditions. Moreover, physical testing is constrained by the availability of materials, equipment, and consistent weather conditions, which can hinder progress and increase costs.

2.4 Role of Computational Fluid Dynamics (CFD) in Solar Dryer Design

Advancements in computational tools have introduced a transformative approach to solar dryer design through Computational Fluid Dynamics (CFD). CFD is a powerful simulation tool that uses numerical methods to analyze and solve problems involving fluid flow, heat transfer, and other related phenomena. By simulating the behavior of air and heat within a solar dryer, CFD allows designers to predict and optimize performance under various conditions without the need for extensive physical testing [8].

CFD enables researchers to model complex interactions within the drying chamber, such as airflow patterns, temperature distribution, and moisture removal rates. This capability is particularly valuable for identifying design inefficiencies and testing alternative configurations. For example, CFD simulations can evaluate the impact of different inlet and outlet positions, solar collector designs, and chamber geometries on drying performance. By providing detailed insights into these parameters, CFD facilitates the development of highly efficient and cost-effective solar dryers.

2.5 Applications of CFD in Solar Drying

Numerous studies have demonstrated the effectiveness of CFD in advancing solar dryer technology. Kumavat [9] used CFD to simulate the temperature and airflow patterns within a solar dryer, identifying optimal configurations for improved drying performance. Similarly, Kumar et al. [10] employed CFD to model and analyze drying parameters under various environmental conditions, showcasing its utility in designing dryers for specific climates and products. These studies underscore the versatility of CFD as a tool for enhancing the efficiency and reliability of solar dryers.

2.6 Integration of Backup Systems in Solar Dryers

One of the challenges of solar drying is its reliance on consistent solar radiation, which can be affected by weather variability. To address this limitation, solar dryers are increasingly being integrated with backup systems, such as incinerators, biomass heaters, or electric heaters. These systems provide supplemental heat during periods of low solar intensity, ensuring uninterrupted drying. For instance, an incinerator can burn agricultural residues or other biomass to generate heat, which is then directed into the drying chamber. This approach not only enhances drying reliability but also promotes the utilization of renewable energy sources.

2.7 Current Study: CFD Analysis of a Solar Dryer with a Backup Incinerator

This study leverages CFD to model and analyze a solar dryer integrated with a backup incinerator. The primary objective is to investigate the temperature distribution within the drying chamber under varying wind velocities, using experimental values for validation. By combining CFD simulations with experimental data, the study aims to:

1. Optimize the design and performance of the solar dryer.
2. Evaluate the effectiveness of the backup incinerator in maintaining consistent drying temperatures.

3. Identify the impact of wind velocity on heat distribution and moisture removal rates.

3. Materials and Methods

The solar dryer with a backup incinerator was fabricated to achieve efficient heat generation, low relative humidity, and enhanced airflow for faster drying. The system comprises three main units: a flat plate collector, an incinerator, and a drying chamber. The incinerator provides supplemental heat during cloudy weather and nighttime.

No-load tests measured air stream temperature, ambient temperature (Ṭa), dry and wet bulb temperatures (Tdb and Twb), relative humidities (RHa and RHd), and average air velocity (Va) using thermometers. Charcoal burned in the incinerator heated water, which flowed by gravity into the drying unit's heat exchanger. Initial and final temperatures were recorded.

On-load tests dried chili peppers (Capsicum annuum) under varying weather conditions (sunny, cloudy, and nighttime). Sun-dried samples served as controls. Drying continued until weights stabilized, as per AOAC (1984) guidelines. No-load tests were conducted from 8:00 AM to 6:00 PM, with data used to evaluate energy and exergy efficiencies.

Modeling and analysis

The solar dryer's 3D model was developed using ANSYS Workbench (3D, pressure-based, standard k-epsilon). Meshing, created in ANSYS ICEM, comprised 95,715 nodes and 522,760 elements. Simulations utilized a 3D segregated solver under steady conditions with an energy equation and k-epsilon viscous model. No-load tests with air as the fluid involved 5,000 iterations, converging between 2,500 and 4,000 iterations.

Boundary Conditions: The computational domain included the solar dryer and incinerator dryer, reflecting experimental dimensions. Glass was used as the solar collector material. Airflow was modeled as three-dimensional, incompressible, steady, and turbulent with constant properties.

4. Results

Results highlight temperature distribution and relative humidity in solar and incinerator dryers. Validation against experimental data was performed. Figure 1 shows the modeled flat plate collector before the simulation.

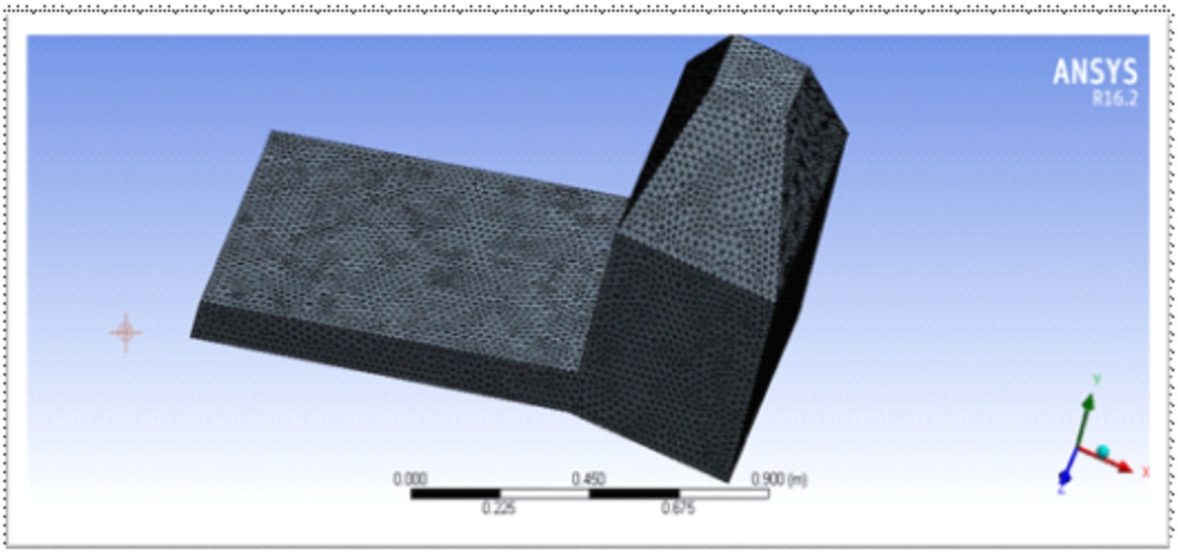


Figure 1: Modeled Flat Plate Collector before Simulation

Figures 2 and 3 Show the maximum absorber plate temperature (76°C) and drying tray temperature (59°C) at 3.5 m/s wind velocity and 495 W/m2 solar radiation. Air stagnation created a hot air pocket at the top of the dryer [8].

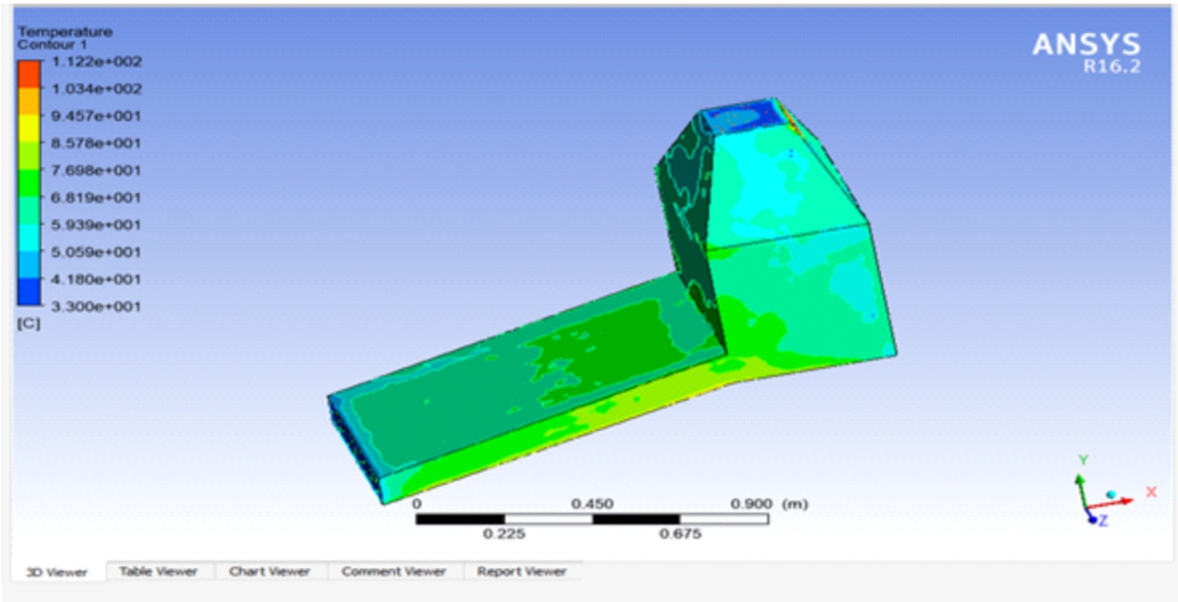


Figure 2: Temperature Contour of Flat Plate Solar Drying

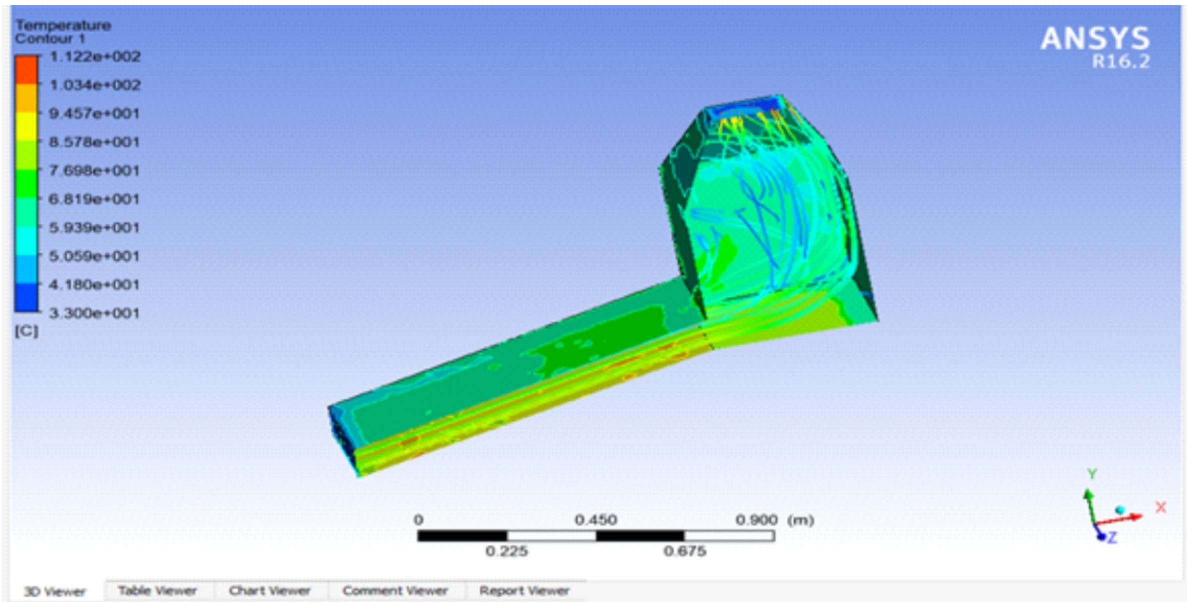


Figure 3: Sectional View of Temperature Contour during Flat Plate Solar Drying

Figure 4 illustrates the velocity distribution in the flat plate solar dryer during the no-load test. The results indicate that air enters the flat plate collector via natural convection at a velocity of 3.5 m/s, with a laminar flow pattern. As the temperature rises, the air velocity increases and circulates around the drying tray in the drying chamber. When a certain amount of pressure builds up in the dryer, the air exits through the outlet vent at a velocity of 10.55 m/s. It is also observed that the flow at the center of the dryer, around the drying chamber, is turbulent because the middle of the dryer provides more space, allowing better circulation and faster drying in that region.

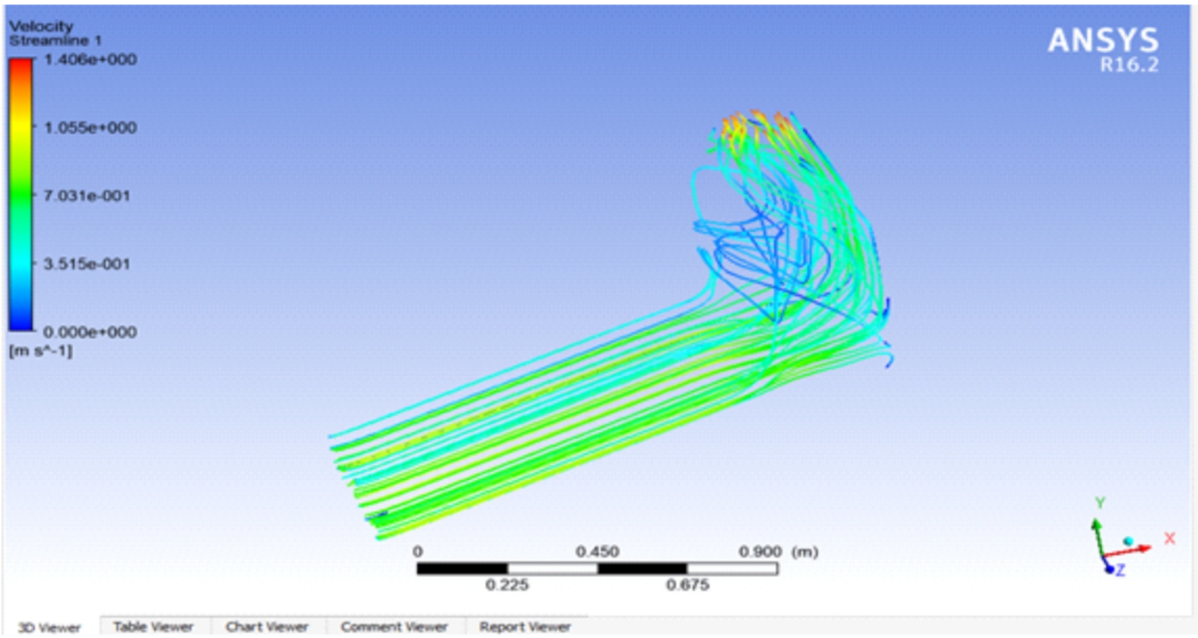
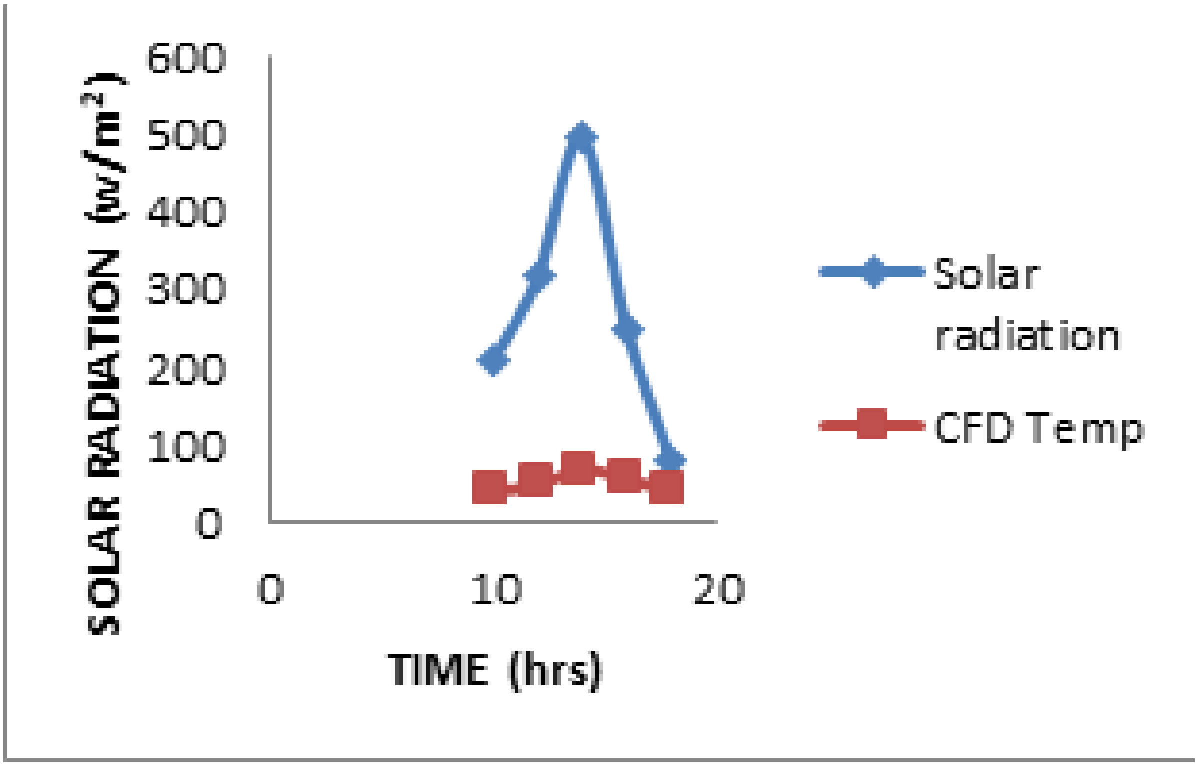


Figure 4: Velocity Contour of the Flat Plate Solar Dryer

Figure 5 shows that experimental and analytical temperature values depend on solar radiation intensity and are directly proportional to it. CFD result values are higher than experimental ones. At 2 pm, when solar radiation reaches its maximum intensity of 495 W/m², the dryer temperatures are 38°C and 68°C for experimental and computational readings, respectively. This difference can be attributed to the fact that actual practice involves some losses and that the properties of the simulated materials differ slightly from those of the locally used materials during experimentation.



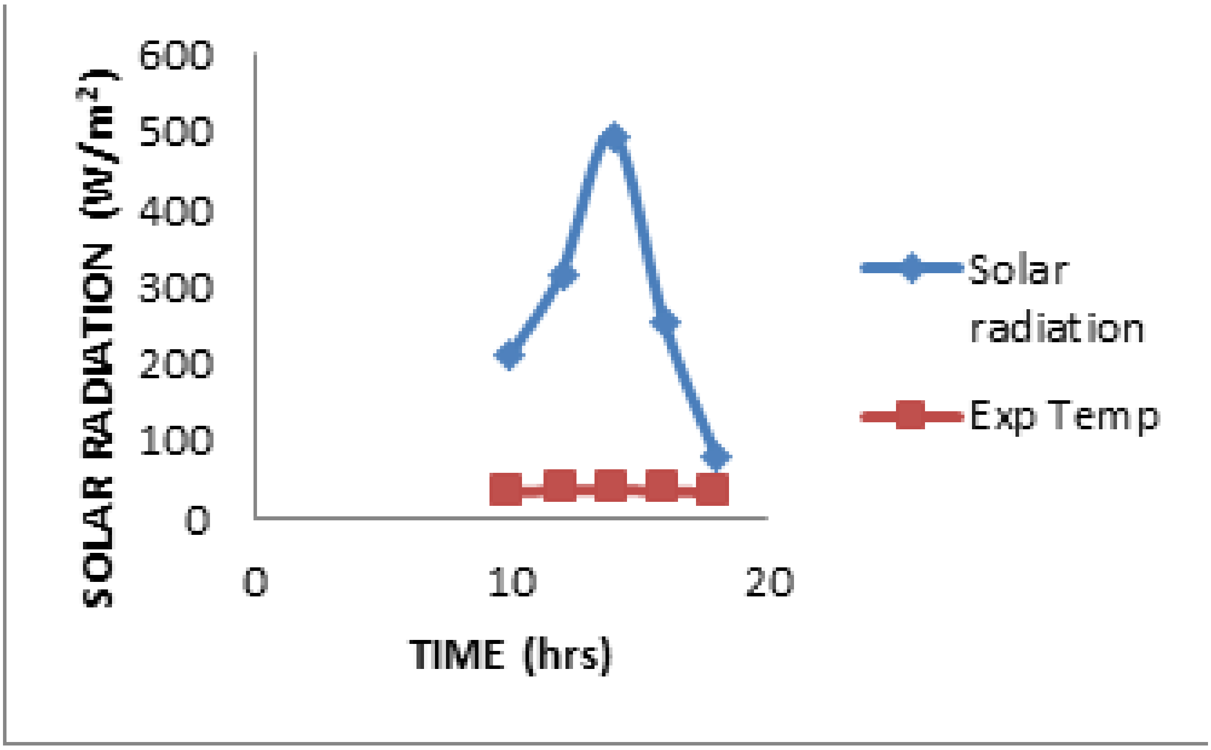


Figure 5: Temperature Variation with Experimental and Analytical Results for Flat Plate Solar Dryer

Figures 6 and 7 present the velocity streamlines of an incinerator dryer and the total temperature contour during incinerator drying, respectively. The dryer was modeled as a system with the incinerator acting as a heat source, supplying heat at a constant rate. The process was assumed to be adiabatic, with no heat gained or lost during operation. The airflow was conventional and maintained constant at the inlet, with a velocity of 2.7 m/s. Results indicate that the airflow in the dryer remains laminar. The temperature distribution was observed to be uniform, maintaining a steady value of 45°C during the no-load test.

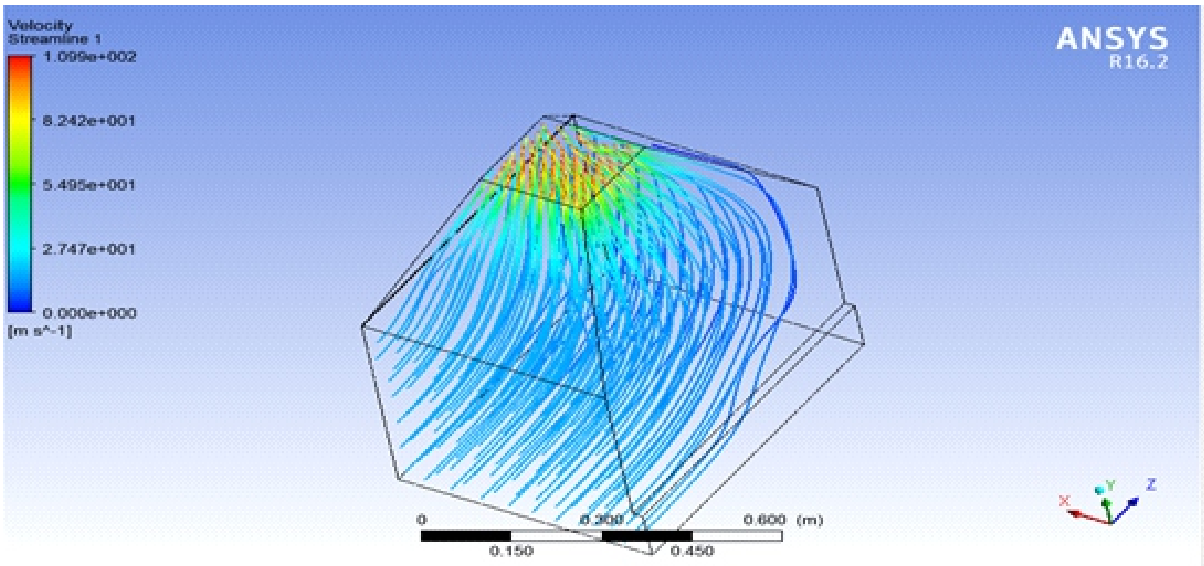


Figure 6: Velocity Streamlines of an Incinerator Dryer

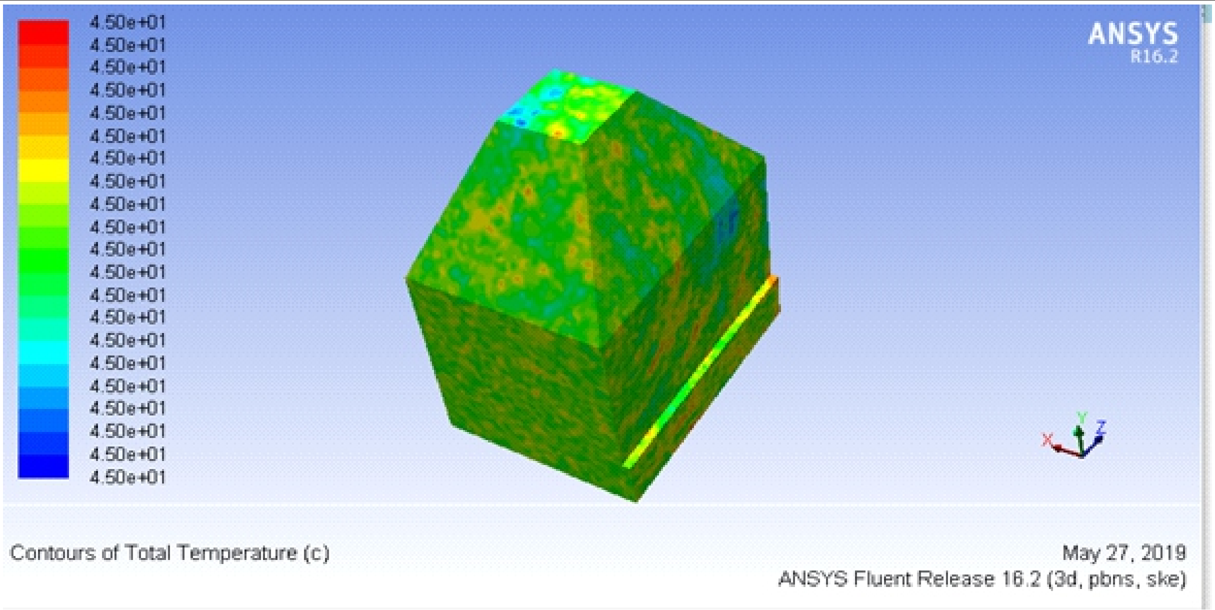


Figure 7: The Contour of Total Temperature during Incinerator Drying

5. Conclusion

CFD analysis of a solar dryer with a backup incinerator was validated against experimental data. Results confirm that CFD temperatures exceed experimental values but follow similar trends, increasing with solar radiation. The dryer performs best on sunny days. Incinerator-assisted drying shows lower temperatures, likely due to heat exchanger losses, but remains a viable alternative for rural drying during cloudy weather and nighttime.

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