

Design, CFD Analysis, and Fabrication of a Solar-Driven Mechanical Crop Dryer with Moisture Regulation

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Abstract:- This study presents the design, fabrication, and computational validation of a solar-driven crop dryer engineered to enhance agricultural preservation by reducing drying time compared to traditional open-sun methods. The prototype utilizes a 2' x 2' x 1.5' wooden enclosure for superior insulation and a polycarbonate sheet to harness solar energy through the greenhouse effect. A 5W solar panel powers a 5V DC fan to facilitate forced convection across three Mild Steel (MS) trays, while manual moisture regulation prevents the stagnation of humid air. Computational Fluid Dynamics (CFD) simulations were conducted to optimize internal airflow and heat distribution. Experimental results demonstrate that the system maintains internal temperatures significantly higher than ambient levels, providing a cost-effective and hygienic solution for small-scale farmers.

I. INTRODUCTION

Traditional open-air sun drying is widely used for agricultural preservation but suffers from slow drying rates, spoilage from unpredictable weather, and exposure to contaminants like dust and insects, resulting in significant post-harvest losses and compromised crop quality. To address these limitations, this project presents the design, CFD analysis, and fabrication of a compact, cost-effective solar-driven crop dryer with manual moisture regulation. Utilizing a 2'x2'x1.5' wooden enclosure topped with a high-transmittance polycarbonate glazing sheet, the system engineered for this investigation establishes a controlled greenhouse effect that maximizes thermal gain and accelerates the dehydration process well beyond traditional timeframes.



Fig.1:- AI Image for representation

II. Experimental Investigations

1. Experimental Setup

The prototype's 2' x 2' x 1.5' footprint balances portability with high-volume capacity. A 5W solar panel powers a 5V DC axial fan to establish forced convection. A manual moisture regulation system, consisting of adjustable slot vents, addresses humidity saturation.

2. Experimental Procedure

1. Sample Standardization:

Fresh red chillies are cleaned and divided into 750g batches. These are spread in a single, uniform layer across the Mild Steel (MS) mesh trays to ensure an equal surface-area-to-volume ratio, which is critical for consistent drying across both drawer compartments.

2. System Setup and Alignment:

The dryer is placed in an open area with the polycarbonate glazing oriented toward the sun to maximize thermal gain. The 5W solar panel is connected to the 5V DC fan, which immediately initiates active forced convection to circulate air through the internal chambers.

3. Diurnal Data Logging:

Over an 8-hour cycle (9:00 AM – 5:00 PM), internal and ambient temperatures are recorded hourly using digital thermocouples. Airflow velocity is monitored at the inlet to ensure a steady flow of approximately 1.2 m/s, consistent with the parameters used in the CFD simulations.

4. Moisture Regulation and Final Validation:

The polycarbonate sheet is monitored for condensation; if detected, the manual slot vents are adjusted to release humid air. The trays are weighed hourly until the crop mass stabilizes at 345g (reducing moisture from 80% to 13%), at which point the physical results are cross-verified against the ANSYS Fluent thermal contour maps.

3. Methodology Adopted

The investigation is structured around the synergy between digital engineering and physical validation, divided into three phases: Virtual Design, Fabrication, and Experimental Testing.

A. Virtual Design & Simulation

- We adopted a CFD-first methodology using a high-fidelity 3D CAD model. The steady-state (k-epsilon) turbulence model paired with a Conjugate Heat Transfer (CHT) solver was used to predict air distribution from the left-wall mounted 5V fan. Boundary conditions were set with an inlet velocity of 1.2 m/s and solar irradiance of 650 W/m².

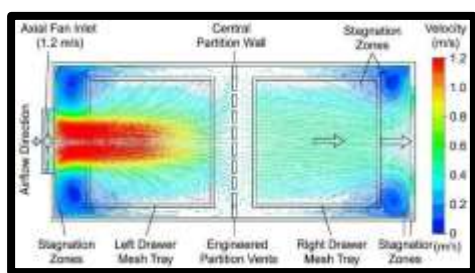
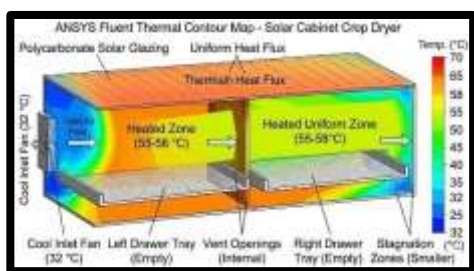


Fig.2:- Velocity vector plot



B. Fabrication and Material Integration

Wood was chosen for the framework to prevent heat loss, while Polycarbonate was selected for the glazing surface due to its superior solar transmittance. The internal architecture features a side-by-side dual drawer tray system with independent sliding drawers structured with 45% open-area MS wire mesh.

III. METHODOLOGY & WORKING PRINCIPLE

Working Principle

The solar-driven mechanical crop dryer operates on the principles of solar thermal conversion (the greenhouse effect) and forced convection mass transfer:

1. Thermal Capture (Greenhouse Effect): High-transmittance polycarbonate glazing acts as a one-way thermal valve. It allows short-wave solar radiation to penetrate the 2' x 2' x 1.5' chamber while trapping long-wave infrared radiation radiating off the black-coated interior surfaces and Mild Steel (MS) trays. This rapidly elevates internal temperatures to a stable 52°C–58°C range.

2. Forced Convection & Evaporation: A 5W solar photovoltaic panel generates electricity to power a 5V DC axial fan mounted on the left side wall. The fan forces a horizontal stream of ambient air at 1.2 m/s through the left compartment, sweeping across the first crop mesh drawer.

3. Continuous Moisture Displacement: The air stream picks up evaporated moisture, flows through engineered partition vents in the central divider wall, passes horizontally through the right drawer compartment, and moves toward the exhaust. This constant exchange prevents air stagnation and humidity saturation, drastically accelerating drying kinetics.

Methodology

The engineering framework is split into three core phases to seamlessly bridge the gap between digital simulation and empirical results:

Phase 1: Virtual Design & Simulation (CFD): Before physical assembly, a 3D CAD model was developed and subjected to steady-state (k-epsilon) turbulence modeling paired with a Conjugate Heat Transfer (CHT) solver. Simulations with a 1.2 m/s inlet velocity and 650 W/m² solar flux verified that airflow diffuses uniformly (0.35 m/s to 0.48 m/s) through the tray beds, successfully eliminating stagnant "dead zones".

Phase 2: Fabrication & Material Selection: A hybrid material structure was built using high-durability, low-thermal-conductivity marine plywood to act as an insulated thermal envelope. The interior was optimized with a central vertical partition wall to split the unit into two balanced, horizontal

side-by-side drawer compartments holding 45% open-area MS wire mesh trays.

Phase 3: Experimental Validation: Empirical testing was conducted over an 8-hour diurnal cycle (9:00 AM to 5:00 PM) using a 1.5 kg batch of fresh red chillies. Digital thermocouples tracked internal thermal profiles to build real-world drying curves, and manual exhaust slot vents were modulated based on visual condensation feedback to maximize evaporation rates. The final results showed a tight numerical convergence with the initial CFD maps within a minimal 6.4% error margin. The governing equations of fluid flow, including the continuity and Navier–Stokes equations, are solved using a pressure-based solver. The SIMPLE

algorithm is employed for pressure–velocity coupling, and convergence criteria are set to ensure solution accuracy. Key flow parameters such as velocity distribution, pressure

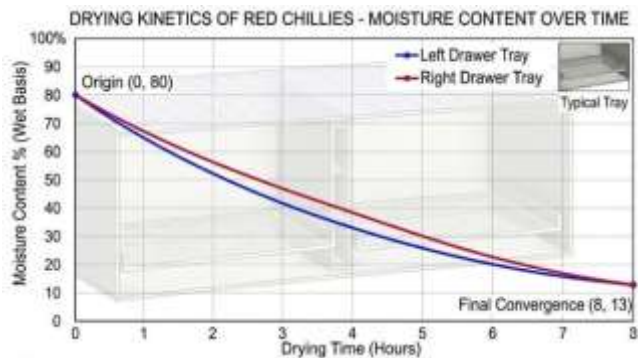
IV. Trails Photos



V. Results

Time Interval	Ambient Temp (°C)	Core Temp (°C)	Inlet Velocity (m/s)
09:00 AM	29.5	38.5	1.18
11:00 AM	32.2	55.4	1.21
01:00 PM	34.0	59.1	1.17
Time Interval	Ambient Temp (°C)	Core Temp (°C)	Inlet Velocity (m/s)
03:00 PM	32.6	52.6	1.18
05:00 PM	30.1	40.0	1.17

The investigation revealed a 60% reduction in drying time compared to open sun drying. On clear days, internal temperatures stabilized between 52°C and 58°C. The experimental curves indicated that moisture content dropped from an initial 80% to a stable dry mass of 13% within an 8-hour cycle.



Moisture Graph

VI. CONCLUSION

The investigation successfully validated that the combination of a wooden thermal envelope, MS tray conduction, and solar-powered forced convection creates a superior drying environment. The system meets technical objectives by reducing drying time by more than half while maintaining a low-cost, sustainable, and hygienic process.

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