
Design of Solar-Powered Cold Box Using Evaporative Cooling and Solar Chimney Effect for off-Grid Areas

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Abstract: *The present research paper investigates the design of a Solar-Powered Cold Box. Because of its low cost and zero pollution, passive evaporative cooling has great potential as an alternative to conventional air-conditioning in rural areas. Solar chimney is a wonderful passive ventilation system as it relies on the sun energy which is a natural driving force. This paper presents a new modeling of an evaporative cooling system. The Solar-Powered Cold Box is operated entirely without electricity, utilizing simple physical phenomenon like evaporative cooling, thermal insulation, and solar chimney-induced natural convection. In this paper, the design and operating principles are discussed in detail. A mathematical model is simplified by the assumption of Heat transfer (conduction + convection), Pressure difference, Latent heat of Evaporation, Thermal expansion of air and Pressure gradient. The study shows that non-electrical solar cold boxes provide a low-cost, eco-friendly, sustainable, and maintenance-free solution for decentralized cold storage. The study describes a theoretical configuration and proposes experimental model.*

Keywords: Solar cold box, evaporative cooling, passive cooling, solar chimney, off-grid refrigeration.

I. INTRODUCTION:

In the developing countries like India, preservation of perishable goods is a big challenge due to limited access to electricity. As per the various agricultural studies, nearly 30–40% of harvested fruits and vegetables are lost before reaching consumers. Solar-based passive cooling systems give a sustainable alternative to conventional refrigeration as conventional refrigeration systems are expensive, energy-intensive, and harmful to the environment.

Refrigeration plays an important role in food security, healthcare delivery, and agricultural sustainability. However, conventional refrigeration systems rely on grid electricity, which is

mostly unavailable or unreliable in remote areas. Besides, electrically powered systems contribute to carbon emissions as well as high operational costs.

Evaporative cooling is a heat and mass transfer process. This process uses water evaporation for air cooling, in which large amount of heat is transferred from air to water, and consequently their temperature is decreased.

Many studies have explored non-electrical cooling systems such as pot-in-pot refrigerators, wind-assisted ventilation systems, and zero-energy cool chambers. Evaporative cooling has been shown to achieve remarkable temperature reduction in dry and semi-arid weather. Solar chimneys have also been widely studied in order to enhance natural ventilation by converting solar radiation into buoyancy forces.

The Solar Cold Box is a passive cooling device which is operated without electrical energy. It uses solar energy indirectly to create airflow and employs evaporative cooling to reduce temperature. The present study focuses on to design a simple, affordable, and eco-friendly cooling system suitable for the people living rural and remote areas.

It is true that limited research integrates evaporative cooling and solar chimney effects into a compact, portable cold box format. This study significantly bridges that gap by developing and evaluating a hybrid passive cooling model. To study the thermal behavior after evaporative cooling a mathematical model has been developed.

II. SYSTEM DESIGN AND METHODOLOGY

Materials Needed:

- **Insulated box:** 1 wooden box with internal dimensions $\approx 45 \times 30 \times 30$ cm
- **Inner cold chamber:** 1 inner clay pot/ a waterproof plastic container lined with terracotta tiles
- **Evaporative medium:** Fine sand (to pack between the pots) (~6–8 kg)
- **Solar collector:** Acrylic sheet 60×35 cm + black-painted metal/aluminum sheet
- **Solar chimney:** black-painted metal pipe with height ≈ 90 – 120 cm, diameter ≈ 8 – 12 cm
- **Air vents:** 2 mesh-covered vents for inlet & outlet, ~6 to 8 cm diameter
- A small bowl/metal cup (for food/medicine storage inside)
- Tray or base plate
- Glue/Clay/Putty for sealing
- Aluminum reflective inner lining

- Water reservoir: 11 L bottle
- Optional: stand for solar chimney tilt, reflective foil (aluminum) to redirect sunlight to collector

Tools:

- Saw (for wood)
- Drill (for vents & holes)
- Paintbrush & black matte paint (heat-resistant recommended)
- Screwdriver, measuring tape,

Steps to build:

Consider the model as shown in Figure 1.

Step 1: - Build the insulated storage box

1. Cut wooden panels to internal dims ~45×30×30 cm.
2. Line interior of wooden box with insulation. Fix in place to reduce heat gain.
3. Prepare a front-opening lid with snug fit. Add small handles on both sides.

Step 2: - Prepare the evaporative cooling chamber

1. Use a clay pot that fits inside the storage box. Place a water tray around base.
2. Fill gap with fine sand. Add water in it so that sand remains moist.
3. Ensure water reservoir (1–2 L) can be refilled from a small tube outside.

Step 3: -Prepare the solar collector

1. Paint a metal/plywood sheet black so that it absorbs light rays from sun.
2. Fix it under a clear acrylic sheet (gap 1–2 cm). The gap between them helps heat the air above black surface. Solar collector feeds warm air into the chimney.
3. This collector should be faces sun so that it directly heated air into the top of the chimney base.

Step 4: -Build the solar chimney

1. Cut a small opening near the top of the insulated pot.
2. Use a metal pipe, paint it black inside and outside. Take care it be dry completely.

3. Fix solar chimney vertically to the collector. Ensure chimney seals completely to avoid large leaks of air.

Step 5: -Make air inlet

1. Drill one inlet mesh vents near the middle of the evaporative chamber on. Diameter ~7–8 cm.
2. Create a duct on inner side so that inlet air must pass through evaporative medium.

Step 6: - Connect insulated storage box to evaporative chamber and solar chimney

1. Ensure cooled air leaving evaporative chamber flows into the storage box. Create an internal opening between the two (6–9 cm).
2. Create an outlet from storage at the top connected to the solar chimney inlet so air exits pass through the solar chimney.

Step 7: - Sealing & finishing

1. Seal all joints to reduce leaks (Don't choke the airflow path).
2. Seal the bottom gaps of insulated box so sand and water doesn't leak.
3. Paint external wooden box surfaces.

Step 8: - Prepare the Base (Optional)

1. Place the entire setup on a tray with water to allow continuous evaporation of water from the bottom.

Working Principle:

The system is operated by three passive mechanisms:

1. Evaporative Cooling:

Small storage box is placed inside a larger insulated storage box. The space between them is filled with wet sand. Air from mesh vents passes through wet surfaces. Water gets evaporated from the outer pot, it absorbs latent heat of vaporization from the surrounding air and reduce the internal temperature. Temperature may drop 9–15°C below ambient temperature.

Let, Q be the heat absorbed by the wet sand,

M be the mass,

L be the latent heat of vaporization, then

When water evaporates from the wet sand, it absorbs heat:

$$Q = m \times L$$

This heat is taken from the inner pot →cooling effect.

2. Thermal Insulation:

Heat gain from the external environment is minimized by insulated walls, maintaining a lower internal temperature for extended periods.

Clay and wet sand slow down heat conduction from outside atmosphere.

3.Solar Chimney Effect:

A tall blackpainted chimney is attached at the top of the wooden box. It absorbs sunlight.Sunlight heats the chimney, making air inside it heats up. As hot air is less dense, it expands and rise upward.

Rising hot air creates pressure gradient inside the pot system.As the hot air escapes, it creates low pressure at the bottom of the chimney. Because of the pressure difference, new air is drawn from the inlet vents into the cooling chamber.

This process creates a continuous airflow.

More airflow = more evaporation = extra cooling.

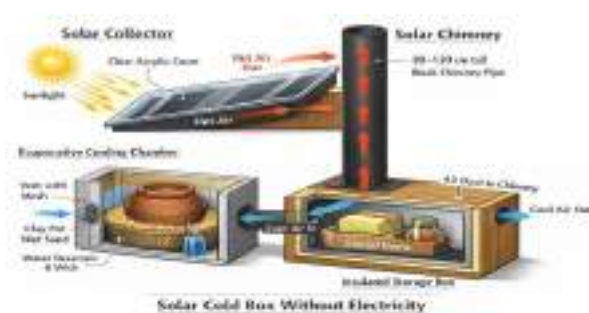


Figure 1:Illustrations showing the structural diagram, airflow mechanism, and evaporative cooling process of solar cold box.

Testing procedure:

1. Fill water reservoir, wet sandthoroughly. The system should be placed facing sun.

2. Place a digital thermometer inside storage and one outside the box. Record both thermometers every 20 minutes for 3–4 hours during peak sun.
3. Expected reduction in temperature: 8–15°C lower than ambient temperature in dry climates. Typical demo claims: 8–12°C drop on clear sunny day. Exact value depends on factors like humidity, wind, solar intensity, and design quality.
4. Airflow can be checked by feeling at outlet or using a small piece of tissue at inlet or outlet. Tissue will flutter toward chimney indicating suction.

Optimization tips:

- Solar collector should be faces sun so that it directly heated air into the top of the chimney base. For demo model, a tilt of 20–30° works.
- Chimney should be as tall as possible within practical limits (90–120 cm) — taller chimney → stronger natural draft.
- Maintain air path: inlet → evaporative chamber → storage → solar chimney outlet. Keep path unobstructed.
- Weak airflow: increase solar chimney height, ensure solar chimney painted black, reduce inlet leaks, widen solar chimney diameter slightly.
- Insufficient cooling: ensure evaporative media remains wet, increase pad surface area, improve insulation, reduce direct heat gain on storage box (shade or reflective cover).
- High humidity days: performance drops — use thicker evaporation pads and increase airflow.
- Water loss too fast: add float valve or controlled drip from reservoir; increase sand depth to store more water.

Safety & practical tips:

- Avoid placing perishable medicines/foods for long periods without monitoring. This system is for preservation, not freezing.
- Use food-safe containers inside storage box.
- Ensure chimney is securely anchored to avoid tipping.
- Keep wooden parts dry and treat against rot if outdoors.

Maintenance:

- Refill water daily in hot/dry climates (less often in humid weather).
- Clean mesh filters weekly.
- Check and repaint chimney if paint peels.

- Replace cloth pads every 3–6 months or when moldy.

Simple parts list + approximate budget (India, 2025, demo scale):

- Clay pot(s): ₹200–400
- PVC pipe/chimney materials & paint: ₹300–500
- Insulation & plywood: ₹400–800
- Acrylic sheet for collector: ₹300–600
- Misc (silicone, mesh, fasteners): ₹200–400
- Estimated total: ₹1,400–2,700 (varies by materials & scale)

Expected Performance:

Under sunny Indian conditions:

2. Ambient Temp: 32–40°C
3. Inside Pot: 18–24°C
4. Best Drop: 12–15°C below ambient
5. Duration: Whole day, continues at night if sand stays wet.

Advantages:

1. Operates completely without electricity
2. Environment-friendly and carbon-free
3. Simple construction using locally available materials
4. Minimal maintenance
5. Suitable for remote and rural regions
6. The model proposed is free-standing and could be built anywhere on open ground.

Applications:

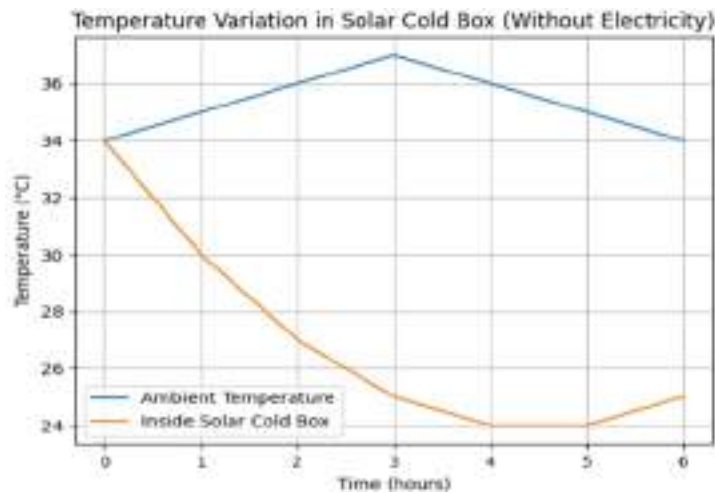
1. Short-term storage of fruits and vegetables
2. Preservation of milk and dairy products
3. Rural healthcare (medicine storage)
4. Agricultural field storage
5. Disaster relief and emergency situations

Result and Discussion:

The expected observations indicate:

1. Internal temperature reduction of 7–18 °C below ambient

2. Maximum cooling observed during peak solar radiation.
3. Improved airflow due to chimney-induced draft
4. Cooling performance decreases with increasing humidity
5. The results confirm that passive solar heating, when combined with evaporative cooling, can effectively produce refrigeration-like conditions without electricity.



Conclusion:

The calculations are purely theoretical. No experimental work has been carried out on the multichannel chimney or on the model proposed.

This research demonstrates that with the help of Solar Cold Box, effective cooling without electricity can be achieved using simple physical principles. The system offers a sustainable, affordable, and scalable alternative to conventional refrigeration for off-grid applications. Future work may focus on advanced evaporative materials, phase change integration, and climate-specific optimization.

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