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Integration of a Carbon Nano-Florets Enhanced Double-Pass Solar Air Heater with Thermochemical Energy Storage for Continuous Space Heating in High-Altitude Military Applications

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Abstract: ***Space heating in high-altitude regions such as Leh-Ladakh remains a critical challenge due to extreme climatic conditions, high energy demand, and heavy reliance on diesel-based systems. These conventional systems not only increase operational costs but also introduce logistical and environmental concerns. Although solar air heaters (SAHs) offer a viable alternative due to abundant solar irradiance, their inability to provide continuous heating limits their effectiveness. This study proposes an integrated thermal system combining a double-pass, double-glazed solar air heater enhanced with Carbon Nano-Florets (NCF) and a calcium chloride ($CaCl_2$)-based thermochemical energy storage (TCES) unit. The NCF coating improves solar absorptivity through enhanced photon trapping, resulting in elevated absorber temperatures. The double-pass configuration increases air residence time, while double glazing reduces heat losses under low ambient temperatures. A comprehensive numerical model is developed using ANSYS Fluent to simulate coupled heat transfer, fluid flow, radiation, and thermochemical reactions. The results demonstrate a significant increase in outlet air temperature compared to conventional systems, enabling efficient dehydration of the storage material during daytime operation. During night-time, the stored energy is released through hydration reactions, ensuring uninterrupted heating. The system achieves charging efficiencies of approximately 30-35% and discharging efficiencies of 70-75%. The findings confirm that the proposed configuration provides a technically feasible and energy-efficient solution for continuous space heating in remote and high-altitude applications.***

Keywords: Solar air heater; Thermochemical energy storage (TCES); Carbon Nano-Florets; High-altitude heating; CFD modelling; Military applications

1. Introduction

Energy security and operational sustainability are critical considerations for military deployments in extreme environments. High-altitude regions such as Leh experience prolonged winters with ambient temperatures often falling below −15°C. The annual heating demand in such regions can exceed 7800 kWh per shelter, making space heating one of the dominant energy requirements.

Currently, heating in these regions is predominantly achieved using diesel-based systems. While effective, such systems impose significant logistical challenges, including fuel transportation to remote locations, vulnerability of supply chains, and increased operational costs. Furthermore, diesel combustion contributes to greenhouse gas emissions and environmental degradation, which is particularly concerning in ecologically sensitive Himalayan regions.

Solar thermal systems offer a promising alternative due to the high solar irradiance available in these regions. Solar air heaters are particularly suitable for defence applications due to their simplicity, freeze-free operation, and compatibility with direct air heating systems. However, conventional solar air heaters (SAH) suffer from low thermal efficiency, limited outlet air temperature, and inability to provide heat during night-time.

To overcome these limitations, two key strategies are required:
1) Enhancement of solar absorber performance
2) Integration with energy storage systems

Recent advancements in nanomaterials have introduced Carbon Nano-Florets (NCF) as a highly efficient absorber coating. The hierarchical structure of NCF enables photon trapping, significantly improving solar absorptivity and reducing reflectivity.

Simultaneously, thermochemical energy storage provides a solution to solar intermittency by storing energy in the form of reversible chemical reactions. Compared to sensible heat storage, TCES offers significantly higher energy density and negligible heat loss during storage.

Research Gap
- Lack of integrated SAH + TCES systems
- Limited application of nanostructured coatings in SAHs
- Absence of studies focused on high-altitude military applications

Objectives
- Develop an NCF-enhanced double-pass SAH
- Integrate with $CaCl_2$-based TCES
- Perform CFD-based analysis
- Evaluate system feasibility for defence use

2. Literature Review

2.1 Solar Air Heater Systems

Solar air heaters (SAHs) are widely used for space heating and drying due to advantages such as freeze resistance, absence of leakage, and direct air heating. However, their performance is limited by the low heat transfer coefficient of air, which reduces energy exchange efficiency [1].

Double-pass solar air heaters significantly improve performance by allowing air to flow twice over the absorber plate (above and below), increasing contact time and heat transfer.

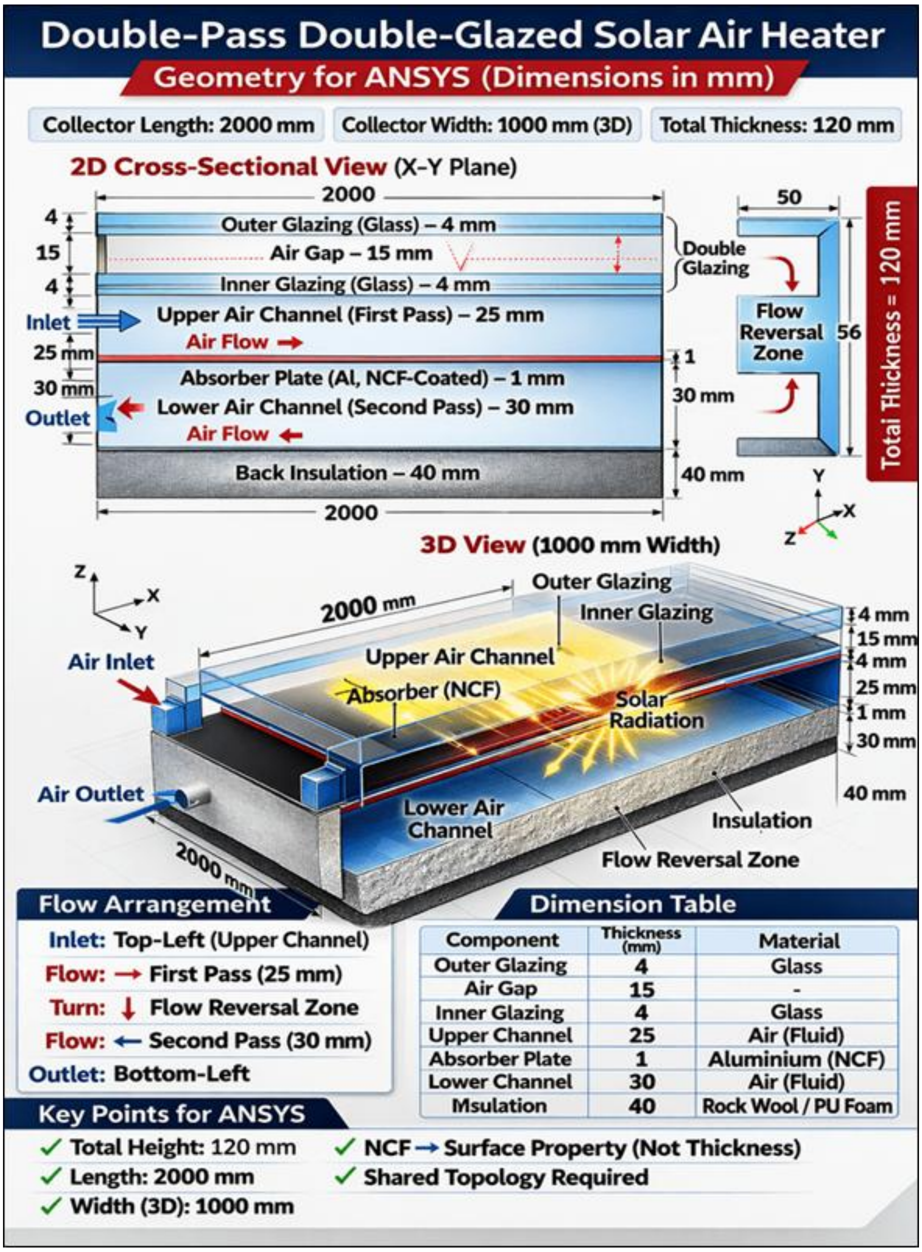
Performance Improvements:

- Increased air residence time
- Enhanced convective heat transfer
- Efficiency improvement of 10-25% over single-pass systems [2]

Limitations:

- Higher pressure drops
- Increased fan power requirement
- More complex design

In high-altitude regions, larger temperature differences enhance heat transfer but also increase heat losses, requiring better insulation.



Component	Thickness (mm)	Material
Outer Glazing	4	Glass
Air Gap	15	-
Inner Glazing	4	Glass
Upper Channel	25	Air (Fluid)
Absorber Plate	1	Aluminium (NCF)
Lower Channel	30	Air (Fluid)
Msulation	40	Rock Wool / PU Foam

Figure 1.1: Double-Pass, Double-Glazed Solar Air Heater

2.2 Double Glazing

Heat loss from the top surface is a major issue in cold climates. Double glazing introduces an additional transparent layer, creating an insulating air gap that reduces losses.

Advantages:

- Reduced convective heat loss
- Lower radiative heat exchange with the sky
- Increased stagnation temperature [3]

Higher stagnation temperature is essential for thermochemical energy storage (TCES) charging.

Trade-off:

- Slight reduction in solar transmittance due to reflection

In cold regions, the reduction in heat loss outweighs optical losses, making double glazing highly effective.

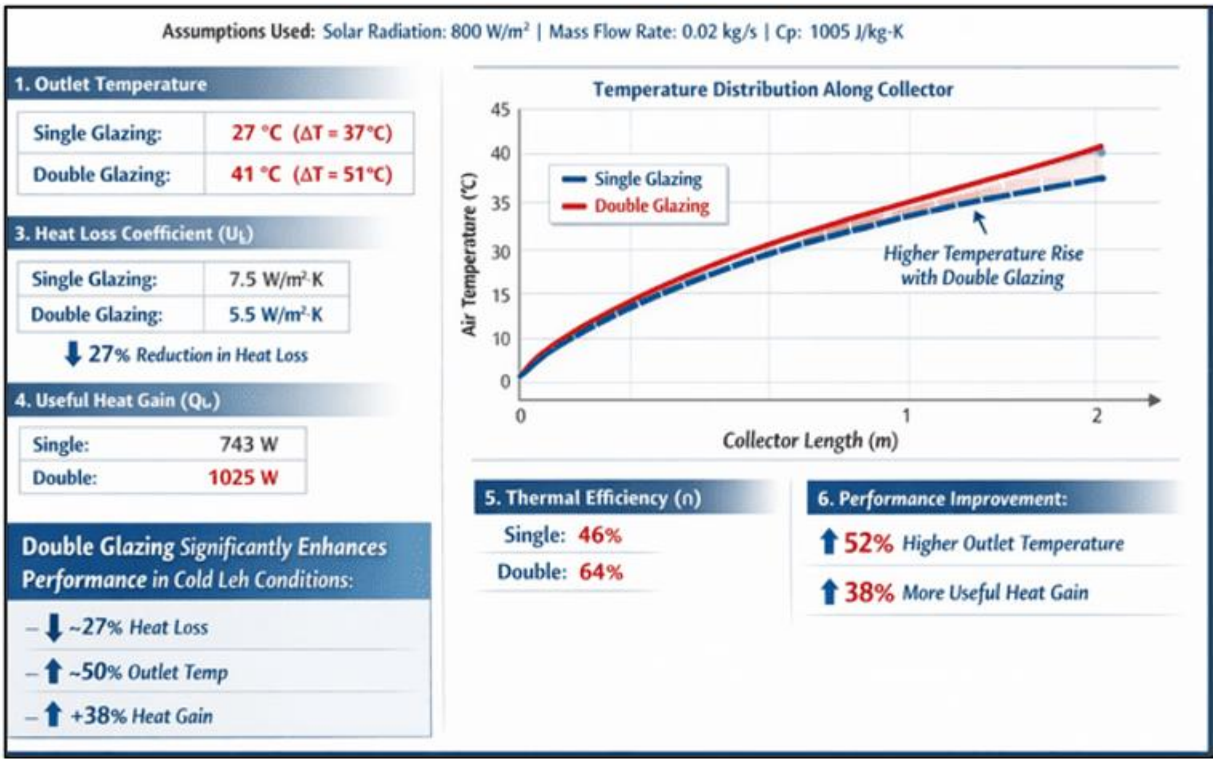


Figure 1.2: Single Glazing vs Double Glazing

2.3 Carbon Nano-Florets (NCF)

Carbon-based nanomaterials enhance solar absorber performance. Carbon Nano-Florets (NCF) have a unique flower-like nanostructure that improves optical absorption.

Optical Enhancement Mechanism:

- Photon trapping through multiple internal reflections
- Reduced surface reflectivity
- Broad-spectrum high absorptivity

Thermal & Structural Advantages:

- High thermal stability
- Resistance to oxidation and degradation
- Mechanical robustness

Comparison with Conventional Coatings:

- Higher and more stable absorptivity
- Better performance under diffuse radiation
- Reduced long-term degradation [4]

NCF coatings are passive and suitable for cold and remote environments.

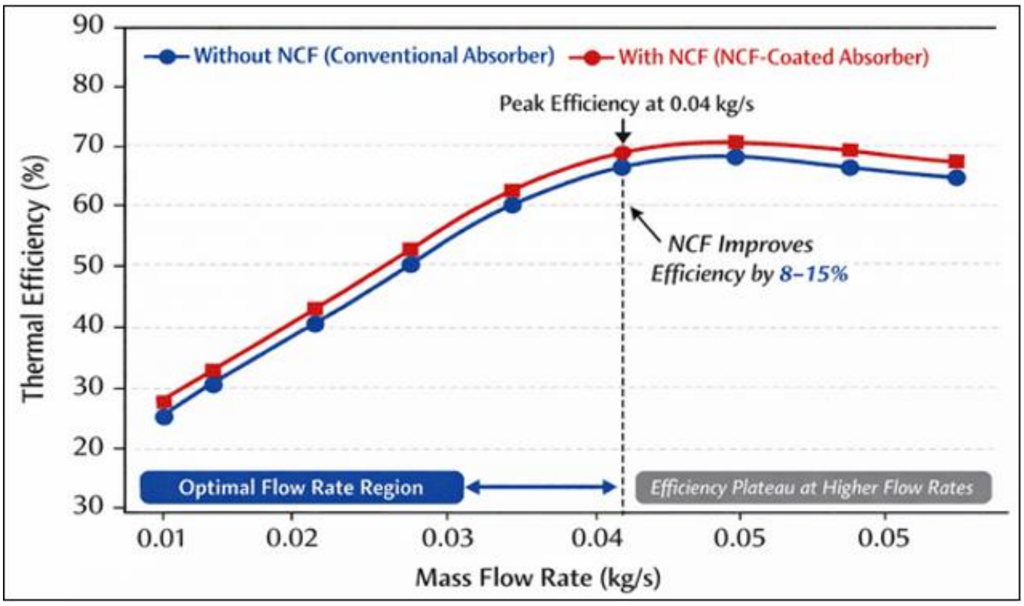


Figure 1.3: Variation of thermal efficiency with mass flow rate for conventional and NCF-coated absorber plates.

2.4 Thermochemical Energy Storage (TCES)

Solar energy is intermittent, limiting nighttime heating. TCES stores energy through reversible chemical reactions, enabling continuous heat supply.

Working Principle:
- Charging: Endothermic reaction stores energy
- Discharging: Exothermic reaction releases heat

Advantages:
- High energy density (4-10× sensible storage)
- Negligible heat loss during storage
- Long-duration storage capability
- Compact design [5]

Challenges:
- Required charging temperature
- Mass transfer limitations
- Material degradation over cycles

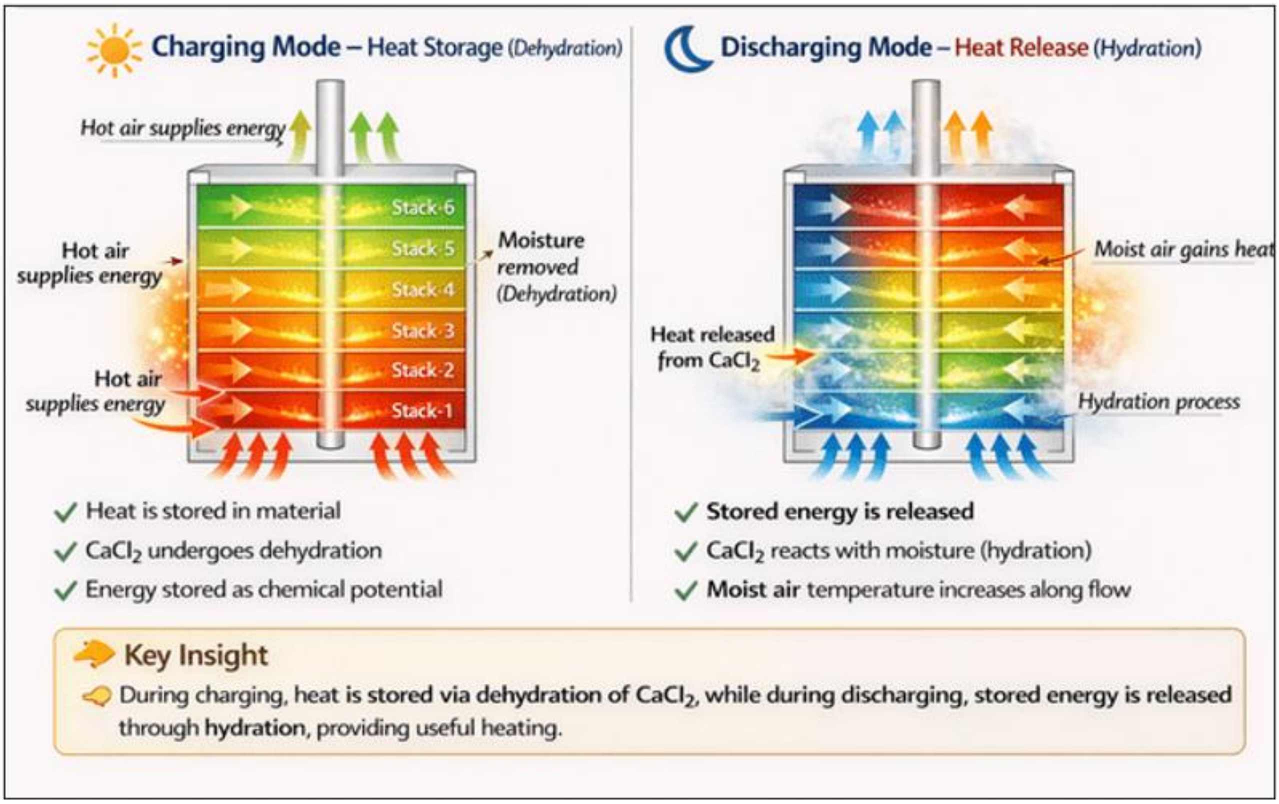


Figure 1.4: Schematic representation of thermochemical energy storage (TCES) showing charging (dehydration) and discharging (hydration) processes using $CaCl_2$

2.5 Material Selection for TCES

Material selection is critical for system performance. For non-concentrating solar air heaters, materials must operate at moderate temperatures.

Calcium Chloride ($CaCl_2$) Advantages:
- Low charging temperature
- High availability and low cost
- Non-toxic and safe
- Favorable reaction kinetics

Comparison:
- $SrBr_2$ offers higher energy density but requires higher temperatures

$CaCl_2$ provides an optimal balance between performance, cost, and reliability, making it suitable for high-altitude and defence applications.

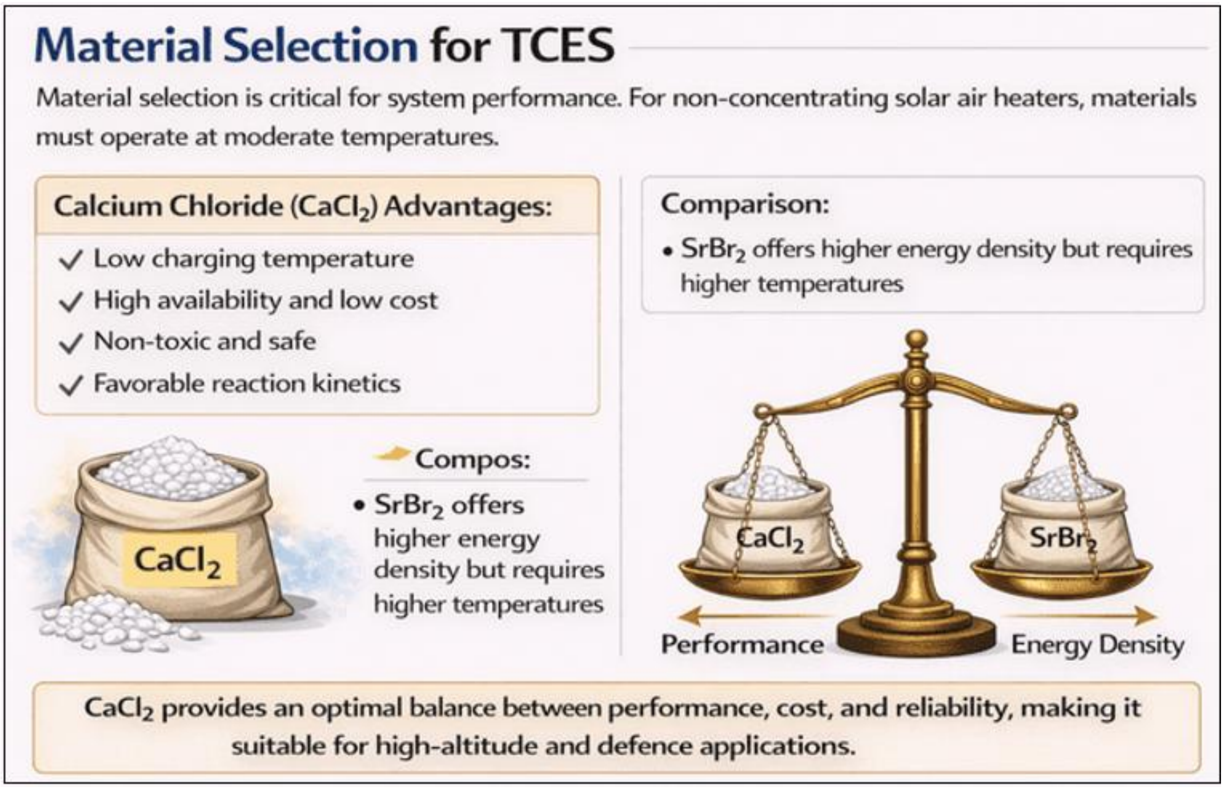


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Figure 1.5: Material selection for thermochemical energy storage (TCES) highlighting advantages of calcium chloride ($CaCl_2$) and comparison with strontium bromide ($SrBr_2$).

3. System Description and Operation

3.1 Overall System Configuration

The proposed system is an integrated solar thermal space heating solution designed for high-altitude regions, combining solar energy collection with thermochemical energy storage (TCES) to ensure continuous heating. It consists of a double-pass, double-glazed solar air heater (SAH), an NCF-coated absorber plate, and a packed-bed TCES reactor using calcium chloride ($CaCl_2$). These components are connected through insulated ducts with a blower and control dampers. The system emphasizes simplicity, reliability, and low maintenance, making it suitable for defence applications. Air is selected as the working fluid due to its freeze-free nature, eliminating antifreeze requirements in sub-zero conditions [6].

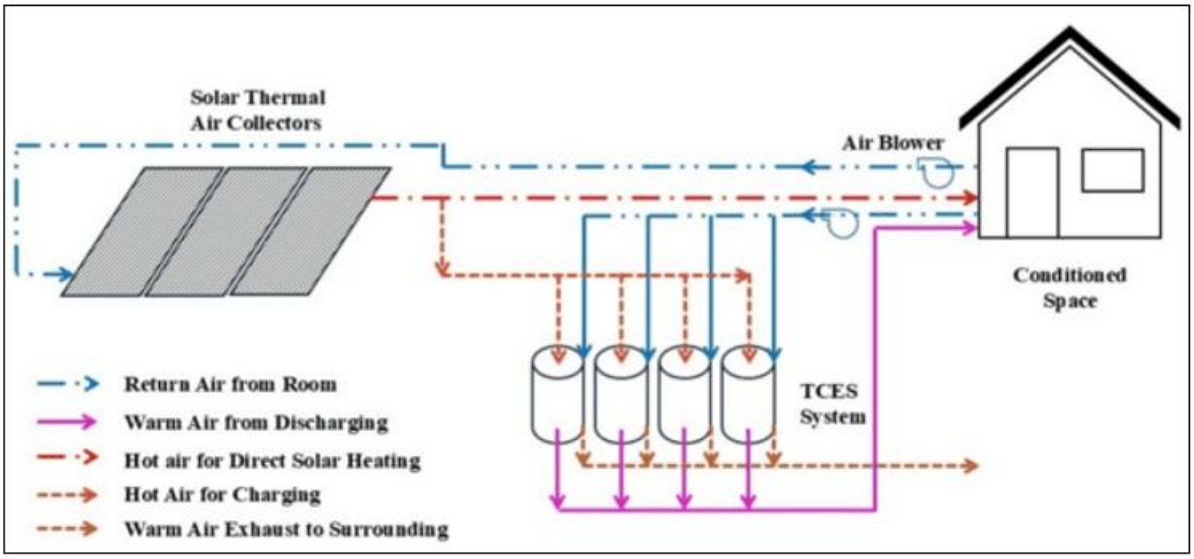

Figure 1.6: Overall system layout of solar air heater integrated with thermochemical energy storage (SAH-TCES) for space heating

3.2 Double-Pass Solar Air Heater

The solar air heater is designed to maximize heat extraction while minimizing losses. It includes double glazing, an upper and lower air channel, an NCF-coated absorber plate, and an insulated back plate.

The airflow occurs in two stages. In the first pass, ambient air flows between the inner glazing and absorber plate, gaining heat through convection and radiation. In the second pass, the air reverses direction beneath the absorber plate, extracting additional heat under reduced loss conditions.

Key advantages:

- Increased air residence time
- Enhanced heat transfer coefficient
- Higher outlet air temperature and efficiency [7]

Double glazing plays a critical role by reducing convective and radiative losses and increasing the absorber temperature. This improves stagnation temperature, which is essential for effective TCES charging [8].

3.3 NCF-Coated Absorber Plate

The absorber plate is coated with Carbon Nano-Florets (NCF) to enhance solar absorption. The nano-structured morphology enables photon trapping through multiple internal reflections, reducing reflectivity and increasing absorption.

This results in higher absorber temperatures and improved convective heat transfer to air. Unlike nanofluids, NCF coatings function passively and do not introduce system complexity.

Major benefits:

- Near-blackbody absorption behavior
- High thermal stability and durability
- No freezing or pumping requirement [9]

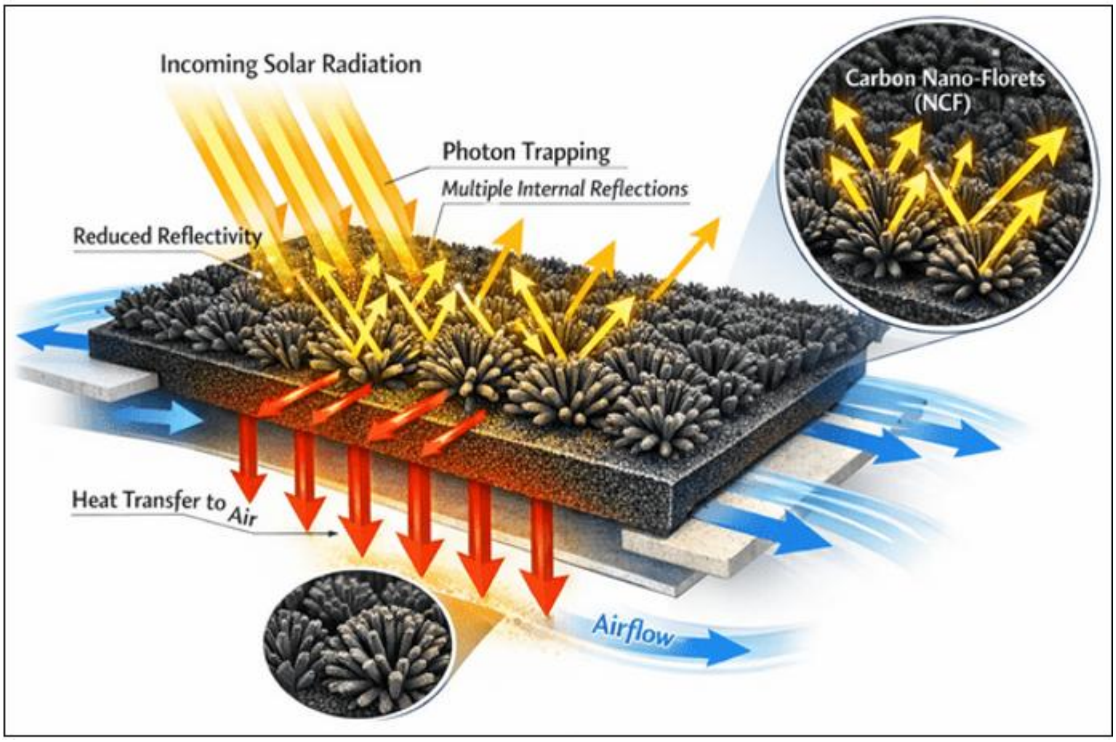

Figure 1.7: Schematic of NCF-Coated Absorber Plate Showing Enhanced Solar Absorption and Heat Transfer

3.4 Thermochemical Energy Storage Reactor

The TCES unit is a packed-bed reactor filled with $CaCl_2$ particles, providing a high surface area and uniform airflow within an insulated casing. The system operates on reversible hydration-dehydration reactions, enabling energy storage and release.

- **Charging (daytime):** Dehydration reaction stores thermal energy
- **Discharging (night):** Hydration reaction releases stored heat

Calcium chloride is selected due to:

- Low charging temperature compatibility
- Cost-effectiveness and availability
- Stable cyclic performance [10]

3.5 Air Flow and Heat Transfer Mechanism

Air serves both as the heat transfer and delivery medium. Heat transfer occurs through multiple modes, including solar radiation absorption by the NCF surface, conduction within the absorber plate, convection to air, and radiation exchange between internal surfaces.

The double-pass configuration enhances interaction between air and the absorber, significantly improving overall thermal efficiency.

3.6 System Operation

During daytime, solar radiation heats the absorber, and air flowing through the collector is heated. The heated air is divided into two streams:

- Direct heating of the space
- Storage in the TCES reactor via dehydration

At night, air passes through the reactor where hydration releases stored heat, ensuring continuous heating. This integration enables day-night operation and reduces dependence on conventional fuels.

Typical performance:
- Charging efficiency: **30-35%**
- Discharging efficiency: **70-75%**

4. Mathematical Modelling

The mathematical model describes the coupled heat transfer, fluid flow, and thermochemical reactions in the integrated solar air heater (SAH) and thermochemical energy storage (TCES) system. To simplify analysis, assumptions include steady-state operation, one-dimensional heat flow, negligible side losses, ideal gas behaviour of air, and thermal equilibrium in the packed bed [11].

4.1 Energy Balance of Solar Air Heater

The useful heat gain is given by:

$$Q_u = \dot{m}c_p(T_{out} - T_{in})$$

The absorber plate energy balance is:

$$I\tau\alpha = h_{pa}(T_p - T_a) + U_L(T_p - T_{amb})$$

Here, NCF coating increases absorptivity (α), while double glazing reduces heat loss coefficient (U_L), improving performance [12].

4.2 Thermal Efficiency

The collector efficiency is:

$$\eta = \frac{\dot{m}c_p(T_{out} - T_{in})}{IA}$$

Efficiency depends on:
- Mass flow rate
- Solar irradiance
- Heat loss coefficient

Double-pass flow enhances heat extraction and overall efficiency [13].

4.3 Stagnation Temperature

Under no-flow conditions:

$$T_{st} = T_{amb} + \frac{I\tau\alpha}{U_L}$$

Higher α (NCF) and lower U_L (double glazing) lead to higher stagnation temperatures required for TCES charging [14].

4.4 Thermochemical Reaction Modelling

The reversible reaction is:

$$\mathrm{CaCl_2} \cdot xH_2O \leftrightarrow \mathrm{CaCl_2} + xH_2O + \Delta H$$

Reaction rate:

$$\frac{d\alpha}{dt} = k(1-\alpha)\left(1 - \frac{P_{eq}}{P}\right)$$

Heat source term:

$$S_q = -\Delta H \cdot n_b \cdot \frac{d\alpha}{dt}$$

4.5 Coupling and Performance

The reactor inlet temperature depends on SAH output:

$$T_{reactor,in} = T_{SAH,out}$$

Key indicators:
- Collector efficiency
- Storage efficiency (≈30-75%)

This coupling ensures effective thermochemical charging and continuous heating [15].

5. Numerical Modelling

A numerical model of the integrated solar air heater (SAH)-thermochemical energy storage (TCES) system is developed using ANSYS Fluent to simulate fluid flow, heat transfer, radiation, and thermochemical reactions under high-altitude conditions. The model solves the governing conservation equations of mass, momentum, and energy to capture the thermo-fluid behavior within the double-pass collector and packed-bed reactor [16].

The airflow inside the collector is modeled using the standard k-ε turbulence model, which provides reliable predictions for internal duct flows with moderate Reynolds numbers. Solar radiation is incorporated using the Discrete Ordinates (DO) model to account for radiation exchange between glazing and absorber surfaces.

The thermochemical reactor is modeled as a porous medium using the Darcy-Brinkman approach, with a heat source term included to represent the energy absorbed or released during chemical reactions.

Key modelling features include:
- Realistic boundary conditions (−10°C to −20°C, 800-1000 W/m² irradiance)
- Mesh refinement near absorber and reactor regions
- Grid independence with variation <3%
- Pressure-based solver using SIMPLE algorithm

Model validation is performed using published data, showing strong agreement with temperature and efficiency trends. The coupling between SAH and TCES is achieved by linking the collector outlet temperature to the reactor inlet condition, enabling accurate prediction of charging, discharging, and continuous heating performance [17].

6. Results and Discussion

This section presents the thermo-fluid and thermochemical performance of the integrated NCF-enhanced double-pass solar air heater (SAH) with TCES under high-altitude conditions. The analysis is based on CFD simulations, focusing on temperature distribution, velocity behavior, and storage feasibility [18].

6.1 Temperature Distribution

The temperature profile shows a continuous rise along the flow direction, with significantly higher outlet temperatures due to the combined effect of NCF coating and double-pass design. The NCF coating enhances absorber temperature through improved solar absorptivity and photon trapping.

The double-pass mechanism further improves heating:

- First pass: moderate heating due to lower temperature difference
- Second pass: higher heat gain due to elevated absorber temperature and reduced losses

Despite low ambient temperatures in high-altitude regions, the increased temperature gradient enhances convective heat transfer, resulting in effective system performance. The temperature rise along the collector follows an exponential trend due to convective heat transfer. The incorporation of double glazing reduces heat losses, while NCF coating enhances solar absorptivity, resulting in higher outlet temperatures and improved thermal performance.

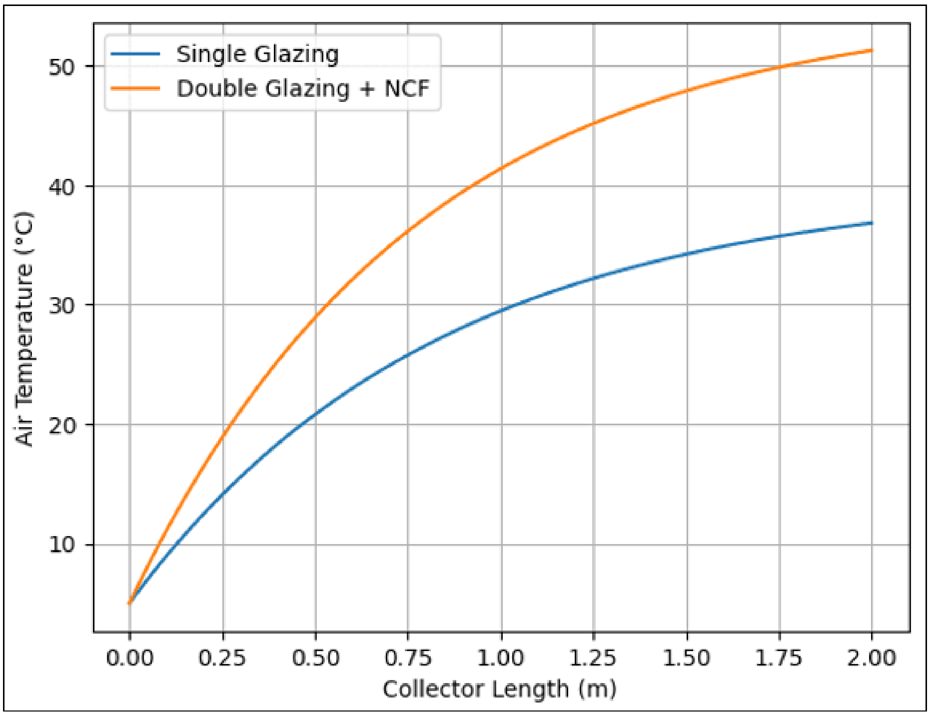

Figure 1.8: Temperature Distribution Along Collector Length Showing Effect of Double Glazing and NCF Enhancement

6.2 Velocity Distribution

Velocity contours indicate a stable and uniform airflow in both channels. Minor turbulence occurs at the flow reversal section, but overall flow remains well distributed.

Impact:

- Uniform heat transfer
- No hot spots on absorber
- Efficient use of surface area

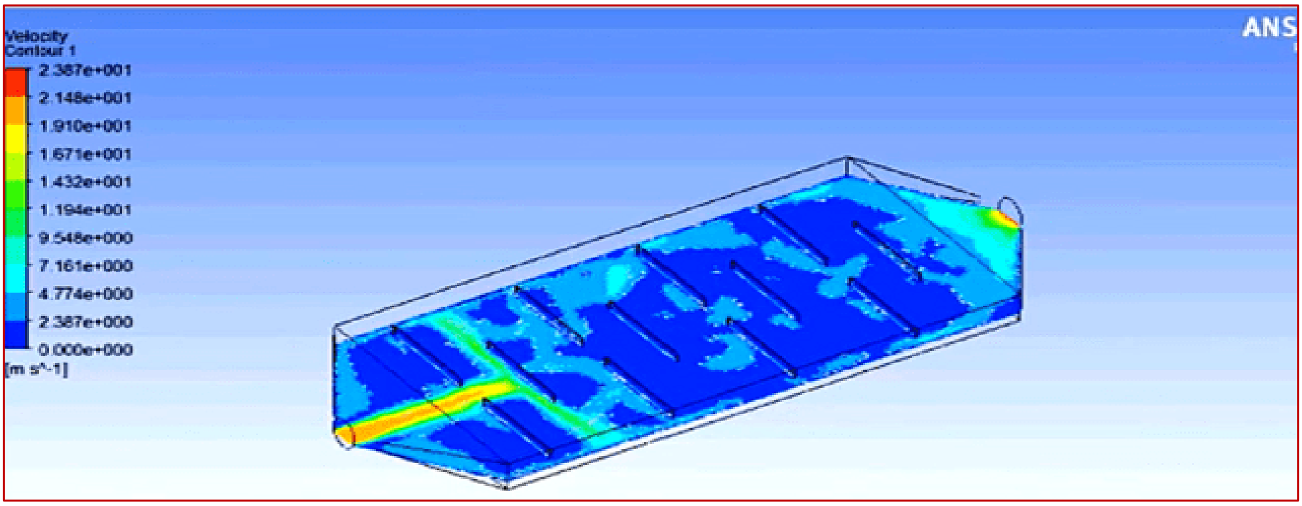

Figure 1.9: Velocity Contours in Double-Pass Solar Air Heater Showing Uniform Airflow Distribution

6.3 Effect of Mass Flow Rate

Mass flow rate significantly affects system performance. Increasing flow rate increases useful heat gain but reduces outlet temperature due to reduced residence time.

Trade-off:
- High flow → better heat transfer
- Low flow → higher outlet temperature

Thus, an optimum flow rate is necessary for efficient TCES charging.

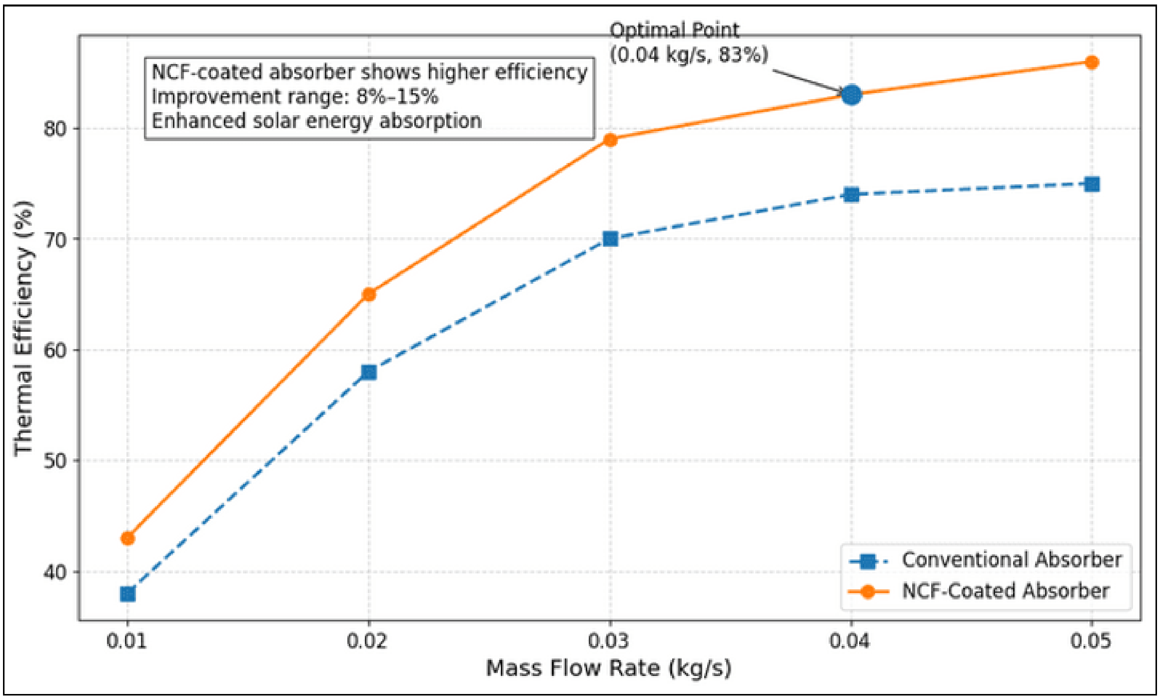

Figure 1.10: Effect of Mass Flow Rate on Outlet Air Temperature and Useful Heat Gain in Solar Air Heater

6.4 Effect of Double Glazing and Nano Carbon Floret

Double glazing reduces heat losses and increases absorber temperature, while NCF coating enhances absorption.

Combined effect:
- Higher stagnation temperature
- Improved thermal efficiency
- Better performance in cold climates

6.5 TCES Performance and Feasibility

The system successfully achieves temperatures required for $CaCl_2$ dehydration, confirming that external heating is not required.

During charging:
- Heat is stored through dehydration

During discharging:
- Heat is released via hydration

Performance:
- Charging efficiency: **30-35%**
- Discharging efficiency: **70-75%**

The higher discharge efficiency is due to the exothermic nature of the reaction.

6.6 Continuous Heating Capability

The integration of SAH with TCES enables continuous heating:
- Daytime: simultaneous heating and storage
- Night-time: stored energy provides heating

This reduces dependency on conventional fuels and ensures reliable operation in extreme climates [19].

7. Performance Analysis

The performance of the integrated NCF-enhanced double-pass solar air heater (SAH) with TCES is evaluated in terms of thermal and exergy efficiency. The system demonstrates a significant improvement in thermal efficiency compared to conventional single-pass SAHs due to enhanced heat transfer and reduced losses [20].

The increase in efficiency is primarily attributed to:
- Double-pass airflow, which increases air residence time and heat extraction
- Double glazing, which reduces convective and radiative losses
- NCF coating, which enhances solar absorptivity and absorber temperature

These combined effects result in higher outlet air temperatures and improved useful heat gain.

Exergy analysis provides insight into system irreversibility and energy quality. The results indicate reduced exergy destruction within the collector due to improved heat transfer mechanisms and better thermal matching between the absorber and airflow.

Key observations:

- Higher exergy efficiency compared to conventional systems
- Reduced entropy generation due to minimized thermal losses
- Improved overall system effectiveness

The integration of TCES further enhances performance by enabling efficient energy storage and utilization. This ensures continuous operation and better utilization of available solar energy, making the system suitable for high-altitude applications [21].

8. Techno-Economic Analysis

The techno-economic performance of the proposed system is evaluated based on cost-effectiveness, energy savings, and environmental benefits. The Levelized Cost of Heat (LCOH) is estimated in the range of **₹31-51/kWh**, making the system competitive with conventional heating solutions, especially in remote and high-altitude regions where fuel transportation costs are high [22].

The integration of solar air heating with TCES significantly reduces dependency on fossil fuels by enabling continuous day-night operation. This leads to improved energy security and lower operational costs over the system lifetime.

Key benefits include:

- Reduced fuel consumption and transportation cost
- Lower greenhouse gas emissions
- Improved sustainability and energy autonomy

Additionally, the system offers long-term economic advantages due to minimal maintenance and absence of fuel price volatility. Overall, the proposed system demonstrates strong techno-economic feasibility for defence and remote applications [23].

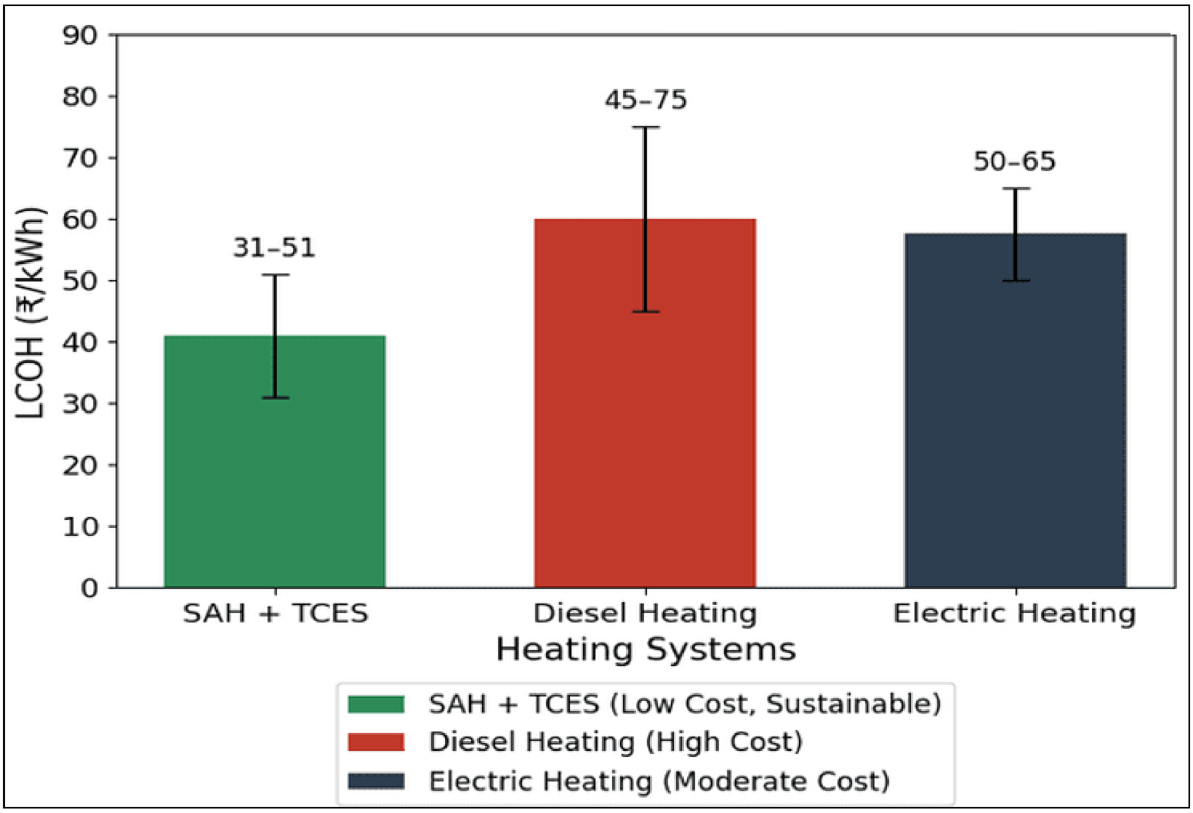

Figure 1.11: Comparison of levelized cost of heat (LCOH) for SAH-TCES and conventional heating system

9. Advantages and Limitations

The proposed integrated solar air heater (SAH) with TCES offers several advantages for high-altitude heating applications. The system enables continuous heating by storing solar energy during the day and utilizing it at night, ensuring uninterrupted operation. Enhanced thermal efficiency is achieved through the combined effects of double-pass airflow, double glazing, and NCF coating, making it highly effective in cold environments. Its reliability, low maintenance, and independence from fuel supply make it particularly suitable for defence and remote deployments [24].

Advantages:

- Continuous day-night heating capability
- High thermal and exergy efficiency
- Suitable for harsh and remote conditions

However, the system also has certain limitations. The initial installation cost is relatively high due to advanced materials and system integration. Additionally, further experimental validation is required to confirm long-term performance and scalability under real operating conditions [25].

Limitations:

- High initial cost
- Need for experimental validation

10. Conclusion

The present study demonstrates the effectiveness of integrating an NCF-enhanced double-pass solar air heater (SAH) with thermochemical energy storage (TCES) for space heating in high-altitude regions. The incorporation of Carbon Nano-Florets (NCF) significantly improves absorber performance by increasing solar absorptivity and reducing reflective losses, resulting in higher absorber temperatures and enhanced heat transfer [26].

The double-pass configuration and double glazing further contribute to improved thermal efficiency by increasing air residence time and minimizing heat losses. The integration of TCES using calcium chloride enables continuous heating by storing thermal energy during the daytime and releasing it during night-time operation.

Key outcomes:
- NCF coating enhances thermal performance and stagnation temperature
- TCES ensures reliable and continuous heat supply
- Improved efficiency compared to conventional systems

Overall, the proposed system demonstrates strong potential for high-altitude and military applications, where reliability, fuel independence, and energy efficiency are critical. The system offers a sustainable alternative to conventional heating methods, with reduced emissions and improved operational autonomy [27].

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