

Enhancing the Thermal Performance of a Three-Pass Solar Air Heater Using Latent Heat Storage Materials: A Comprehensive Review

Enas Khudhayer Obayes, Rafel Hekmat Hameed

University of Babylon, College of Engineering, Department of Mechanical Engineering

Abstract: with latent heat storage materials (Phase Change Materials, PCMs) are reviewed to improve the thermal conductivity. The principle behind this integration is based on the high energy-storage density of PCMs, whose heat absorption and heat release occur at nearly constant temperatures, that enhances the system efficiency and smooths the convergence of the outlet air temperature. The enhancement of the air residence time and heat transfer rate is achieved by the three-pass flow pattern although more pressure drop and design complexity are introduced. A review of literature reveals that the use of PCMs brings about considerable improvement in the total thermal performance as compared to the conventional systems more so by way of prolonging the heating duration beyond the retardation of solar radiation. Proper PCM melting temperature and high thermal conductivity of PCM are important for efficient charging/discharging processes. Major obstacles are the low thermal conductivity of typical PCMs which generally needs to be enhanced by means of fins, metal matrices or by encapsulation methods. The core technical difficulties are the very low thermal conductivity of the ordinary PCMs, which usually needs to be enhanced by fin, metal matrices, or encapsulation methods. Leakage during melting and long-term material stability are also importantly design issues. Moreover, the hydrodynamics of the three-pass configurations becomes increasingly intricate., thus rendering the airflow distribution and pressure drops as the dominant system optimization parameters. The literature on PCM incorporated three-pass heaters is still scarce, as the most of the works related to that of single- or double-pass collectors. There are important gaps in dynamic modeling of multi-pass systems with PCM, long-term cycling studies, and cost – benefit analyses. The review emphasizes the requirement of development of advanced numerical models, superior PCM composites with enhanced conductivity and system level integrated designs that can include reasonably complexity in thermo-technical performances. To sum up, the incorporation of latent heat storage materials into three-pass solar air heaters offers an attractive way to enhance the heat transfer performance, meanwhile, further work is required to solve the material, design and economic issues for large scale implementation.

Keywords: Phase Change Materials, Three-Pass Solar Air Heater, Thermal Energy Storage, Heat Transfer Enhancement, Solar Thermal Systems.

1. Introduction

Solar energy is a highly potential energy source that can easily meet the increasing demand for electricity and thermal energy in the world [1]. Solar collectors Among the different means of harnessing solar energy, solar air heaters (SAHs) are increasingly being used to supply a low- to medium-temperature heat source for industrial drying, space heating, and a wide range of

agricultural applications. These devices collect solar energy and convert it into heat which is then transferred to air passing through the system, further, the warm air can be used on site or stored for later use. [2].

Conventional single-pass solar air heaters are relatively low cost due to their simplistic geometry and ease of fabrication. However, they also have many shortcomings, including poor thermal performance, insufficient heat transfer and severe temperature variations, particularly under intermittent solar radiation. In order to alleviate these disadvantages, multi-pass solar air heaters, especially three-pass configurations, have been introduced[3]. In such designs, the air flows in multiple channels which breaks up the flow and increases the contact time of the air with the absorber surface and convective heat transfer. Therefore, three-pass SAHs provide higher outlet air temperatures, improved thermal uniformity, and better overall efficiency [4]Several parameters such as the design of the absorber plate, the shape of the channel, the flow rate of air, the insulation, and the ambient conditions have an impact on the efficiency of the SAHs. A number of investigations have been conducted to utilize fins, baffles and corrugations to produce turbulence and enhance the heat transfer coefficient. Furthermore, the incorporation of thermal energy storage (TES) materials, especially phase change materials (PCMs), has recently drawn increased interest[4]. PCMs accumulate energy in the latent heat when melting and release it when solidifying, which leads to a reduction in the fluctuations of outlet air temperature and prolonging the hours of operation of solar air heaters beyond sunshine. [5].

Phase change materials can be divided into organic, inorganic and eutectic, with their own unique thermal and physical characteristics. Organic PCMs, such as paraffins, are chemically stable, nonreactive and readily available but exhibit low thermal conductivity .[6] Conversely, salt hydrates, a group of inorganic PCMs, possess high latent heat of storage, but they can also corrode and undergo phase segregation. Eutectic PCMs offer adjustable melting points, but meticulous choice is important to guarantee long-term stability. The choice of a suitable PCM is influenced by considerations such as melting temperature, latent heat capacity, thermal conductivity, chemical stability and cost [7]. [Application of PCMs in three-pass SAHs could be via macro-encapsulation, micro-encapsulation, or shape-stabilized methods. These techniques avoid leakage, enhance heat transfer rate and enable efficient cycling between charging and discharging for several cycles. Furthermore, high performance designs frequently integrate PCMs with high conductivity additives such as metal foams or graphite matrices for even greater thermal performance[8].By incorporating PCMs effectively in the second or third pass of a three-pass SAH, the system is capable of sustaining a constant air outlet temperature, and realizes improvements in energy storage density and reduction in thermal losses[9].

A recent study presents the three-pass configuration with the latent heat storage as a promising solution for the high thermal efficiency, uniform temperature field and long working time[10]. The improved performance allows these systems to be applied to industrial drying, food processing, space heating, and remote applications. In addition, it is worthwhile to mention that further enhancements in heat transfer and system performance can be expected through optimization of geometric parameters, air flow rates, and the properties of the PCMs, which will make the present design both practical and economical[11]. [The present review paper is intended to give an overall review on the improvement of thermal performance of the three pass solar air heaters by using latent heat storage materials. 5, 9, 10 and 11 reviews the design philosophy, heat transfer mechanism, phase change material properties, encapsulation methods and the system arrangements. In addition, comparative studies of various SAH designs, thermal performance analysis in different operating conditions, and an overview of future research topics are discussed.By surveying and...synthesizing representative recent researches, this paper attempts to serve as a basis for the development of more effective, efficient, and enviable solar air heating (SAH) systems with the potential for improvedenergy storage characteristics from the...view of both researchers and engineers.[12].

Rising demand for green and clean energy solutions as well as development of PCMs and multi-pass SAH designs highlight the relevance of applying the latent heat storage in solar air heaters. Such integration increases the robustness and effectiveness of solar thermal systems and also plays a vital role in decreasing the dependency on fossil fuels and harmful greenhouse gases [13]. With the energy demand around the world increasing day by day, performance enhancement of solar air heater by novel design coupled with energy storage continues to be in demand from research as well as application point of view. [14].

2. Three-Pass Solar Air Heater: Concept and Design

A solar air heater (SAH) is an heating system that uses solar energy to heat air that can be then used for space heating and/or drying. In the classical single-pass solar air heater, the air flows over the absorber plate, which is flat or corrugated, in a single pass. Simple as they are, these designs are often characterized by poor thermal performance due to minimal air-surface contact time. Multi-pass solar air heaters, such as three-pass configurations, have been developed to enhance the performance. In such systems, the 3P-SAH air flows over three different channels in succession, which results in greater heat transfer and higher outlet temperatures. The extra passes extend the residence time of air in the heater so that more energy can be absorbed by the air from the absorber plate. [15].

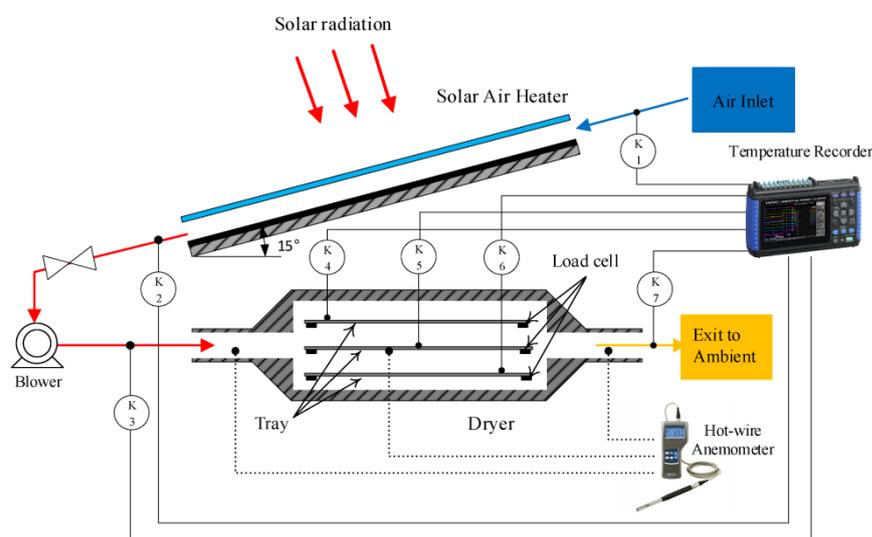


Fig (1): Three-Pass Solar Air Heater[15]

2.1 Working Principle

Three-pass solar air heater consists of the following parts [16]:

1. **Transparent Cover:** It is a barrier that transmits solar radiation and reduces convective heat loss.
2. **Absorber Plate:** For efficient absorption of solar energy, it is generally constructed of high thermal conductivity material such as aluminum or copper.
3. **Airflow Channels (Three Passes):** These channels bathe the air on the top and the bottom of the absorber plate (or multiple times) to increase heat transfer to the air.
4. **Insulation:** Withdraws the heat flow on the rear and two sides of the heater.
5. **PCM Layer (Optional):** It accumulates latent heat and discharges it when the solar radiation level drops, thus preventing outlet air temperature from fluctuating. The process of operation can be described as follows [17]:
 1. **First Pass:** The ambient incoming air in the first channel receives heat from the absorber plate. Because of the heat absorption, temperature increase is moderate.
 2. **Second Pass:** Air changes

flow direction or moves back beneath a secondary absorber channel and receives more heat. When a PCM layer is added, the air melts the PCM partially, storing thermal energy.

3. Third Pass: The air goes through the final channel and has finished absorbing heat. The PCM may release stored latent heat to maintain a constant air temperature during intervals of weak solar radiation.

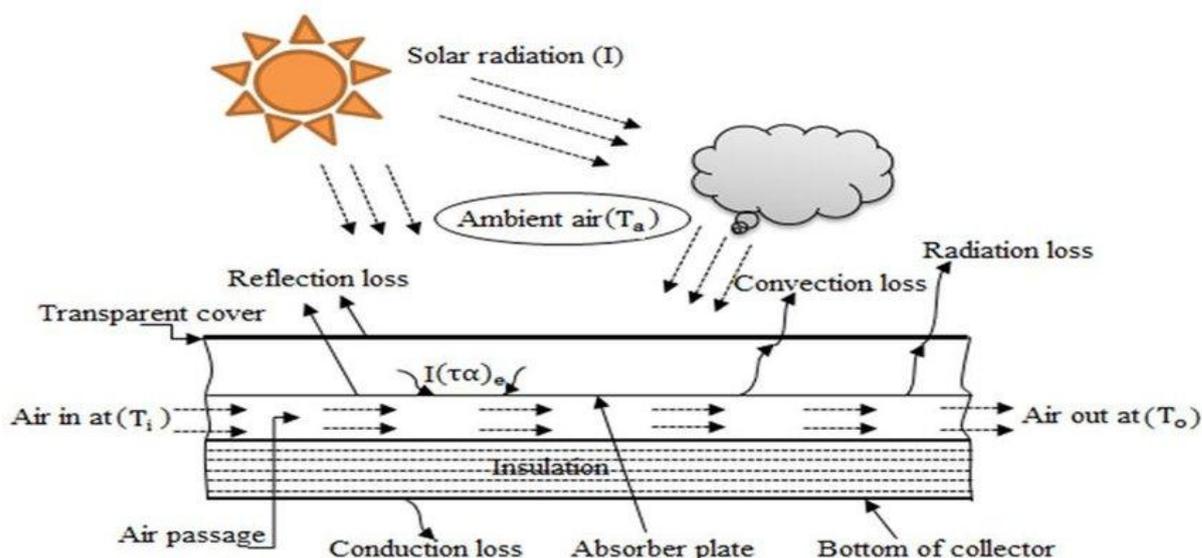


Figure (2): Textual Illustration of Three-Pass SAH Airflow[17]

The air passes three times, increasing contact with absorber surfaces. The optional PCM layer acts as latent heat storage to reduce outlet temperature fluctuations.

2.2 Design Considerations

Designing an effective three-pass solar air heater involves several key parameters[18]:

Table 1: Effective three-pass solar air heater involves several key

Parameter	Description	Typical Range / Values
Channel Depth	Distance between absorber plate and top/bottom covers	20–50 mm
Channel Width	Width of air passage per pass	50–200 mm
Flow Rate	Air mass flow rate through the system	0.02–0.1 kg/s·m ²
Absorber Material	High thermal conductivity metals	Aluminum, Copper
Insulation Thickness	Reduces heat loss from back and sides	25–50 mm
Transparent Cover Material	Allows solar radiation, reduces loss	Glass (4–6 mm) or Polycarbonate
Number of Passes	Multi-pass enhances heat transfer	2–4 passes (3-pass optimal)

Advantages of the Three-Pass Design- Higher thermal efficiency due to the longer air contact time- Uniform outlet temperature which reduces temperature variations- More efficient use of the absorber plate area- Compatible with PCMs and fins to boost energy storage and heat transfer.

Flexibility for space heating, drying and industrial use

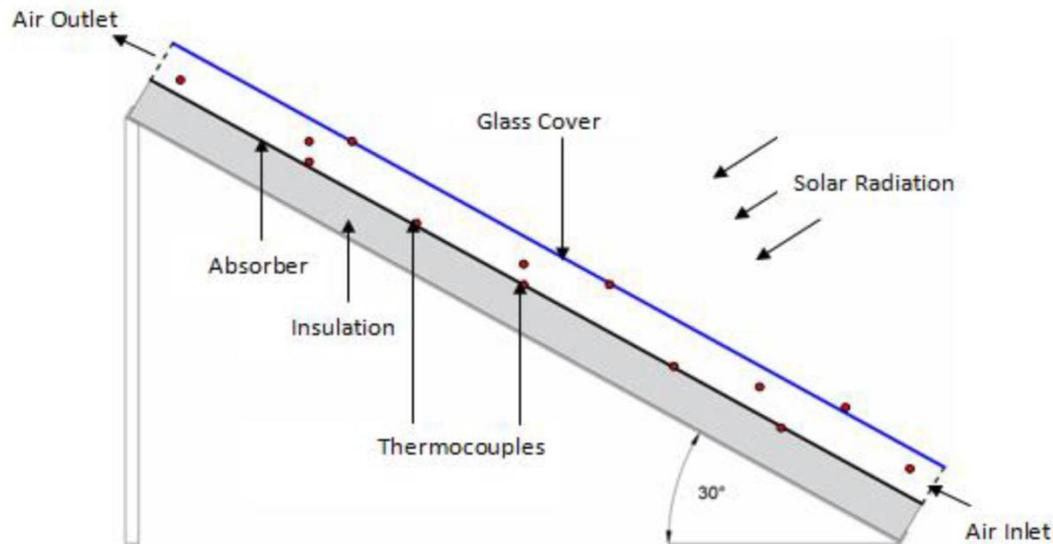


Figure (3): Air Temperature Distribution Across Passes (Textual Representation)

Air Temperature (°C)

 Pass 1: 30 → 45

Pass 2: 45 → 60

Pass 3: 60 → 70

With PCM:

Pass 1: 30 → 45

Pass 2: 45 → 60

Pass 3: 60 → 65 (PCM absorbs excess heat)

Evening:

Pass 3: 65 → 60 (PCM releases stored heat)

- ✓ Without PCM, the third pass may overheat air during peak sunlight.
- ✓ With PCM, outlet temperature is stabilized, improving thermal comfort or drying consistency.

2.4 Typical Configurations

Three pass SAHs can be made with different arrangements [19]:

1. Straight Multi-Pass: Air flows in a straight line and back over flat absorber plates.
2. Corrugated Absorber: It increases the turbulence and the heat transfer enhancement.
3. Fin-Assisted Passes: Each pass contains vertical or horizontal fins that enhance convection.
4. PCM-Integrated: The PCM-based latent heat storage layer for thermal stabilization in the second or third pass.

2.5 Heat Transfer Analysis

The thermal performance of a three-pass SAH depends on [20]:

1. Conduction through absorber and PCM layer
2. Convection between air and absorber surfaces

3. Radiation losses from transparent cover and absorber

The overall heat transfer coefficient (U) can be expressed as:

$Q=U \cdot A \cdot (T_{abs}-T_{air})$ Where:

Q = heat transfer rate (W)

U = overall heat transfer coefficient (W/m²·K)

A = absorber area (m²)

T_{abs} = absorber plate temperature (°C)

T_{air} = air temperature (°C)

Integrating PCMs reduces temperature fluctuations, improving effective heat transfer and outlet temperature stability[21].

The three-pass design in solar air heaters leads to better thermal performance than single-pass solar air heaters due to the fact that: 2.With longer interaction time of the air and absorber 3.Uniformity of the outlet temperature is enhanced.

1. With latent heat storage (PCM) integration/Enable integration with latent heat storage (PCM) 5.Permitting geometry optimization through fins, corrugation and flow alterations
2. Through optimization of channel sizes, flow velocities, absorber material, and insulation, three pass SAHs for industrial and domestic applications can be realized with high efficiency, proven long-term performance, and practical usability.

3. Latent Heat Storage Materials (Phase Change Materials – PCMs)

The improvement of solar air heater (SAH) performance with thermal energy storage is necessary and it is more effective in case of multi-pass types. Latent heat storage based on phase change materials (PCMs) is particularly efficient as it can store a large amount of energy at a nearly constant temperature compared to other storage schemes.Sensible heat storage relies only on temperature change, but by undergoing phase changes (typically solid–liquid), PCMs absorb or release energy, thus resulting in higher energy density per unit volume. [22].

3.1 Working Principle of PCMs

PCMs are based on the latent heat principle that heat is absorbed during the phase change from solid to liquid (melting/charging) and released during the phase change from liquid to solid (freezing/discharging).Charging Process (Melting)[23]: 1.Air heated by solar radiation is flowing through the PCM layer.2.PCM melts by absorbing energy, and stores latent heat. Discharging Process (Solidification): When solar radiation decreases (evening or cloudy days),(the PCM is solidified by releasing its stored heat to the air, so that they maintain a more consistent outlet temperature.

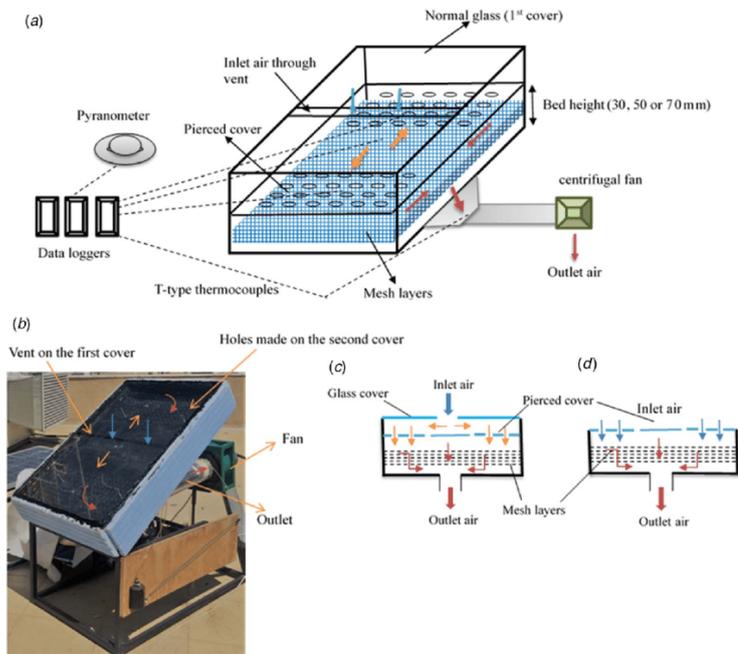


Figure (4): Textual Illustration of PCM Charging and Discharging

3.2 Classification of PCMs

PCMs are generally categorized into three main types[24]:

Table 2: PCMs are generally categorized into three main

PCM Type	Examples	Advantages	Disadvantages
Organic	Paraffin, Fatty Acids	Chemically stable, non-corrosive, no supercooling	Low thermal conductivity (~ 0.2 W/m·K), flammable
Inorganic	Salt Hydrates ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$)	High latent heat, high thermal conductivity	Phase separation, supercooling, corrosive
Eutectic	Mixtures of salts or organic compounds	Tailorable melting point, customizable for specific applications	Compatibility issues, complex preparation

3.3 Key Properties of PCMs for SAHs

Selecting a PCM for integration into a three-pass solar air heater requires consideration of multiple thermal, physical, and chemical properties[25]:

Table 3: Properties of PCMs for SAHs

Property	Description	Ideal Value/Range
Melting Temperature (T_m)	Should match desired air outlet temperature	40–70°C
Latent Heat of Fusion (L_f)	Amount of energy stored per unit mass	High (~ 150 – 250 kJ/kg)
Thermal Conductivity (k)	Rate of heat transfer	Moderate, enhanced with fins or foams
Density (ρ)	Energy storage per unit volume	High for compact design
Specific Heat (C_p)	Energy stored sensibly	Moderate (~ 2 kJ/kg·K)

Chemical Stability	Repeated cycling	$\geq 500-1000$ cycles
Corrosiveness	Effect on containment	Low or none
Cost	Economic feasibility	Moderate

3.4 Integration of PCMs in Three-Pass SAHs

PCMs can be incorporated into SAHs using several approaches[20]:

1. Macro-Encapsulation: PCM stored in containers or tubes within the airflow channel.
2. Micro-Encapsulation: PCM enclosed in small polymer shells, providing high surface area.
3. Shape-Stabilized Composites: PCM absorbed into porous matrices (graphite, metal foam) to prevent leakage.

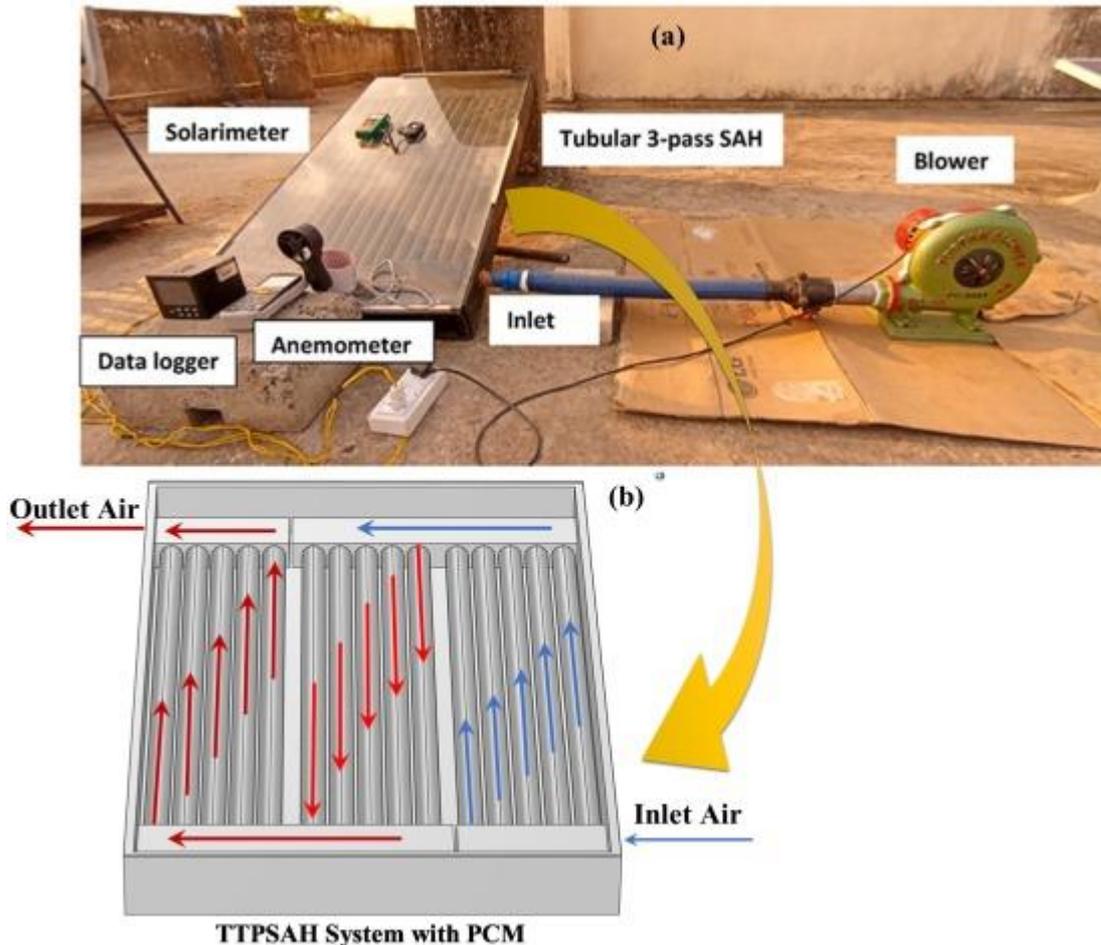


Figure 5: Textual Representation of PCM Integration in 3P-SAH[25]

PCM is generally placed in the second or third pass, where airflow is slower and temperature variation is moderate.

Enhances energy storage and reduces temperature fluctuations during low solar periods.

3.5 Enhancing Thermal Conductivity

A typical drawback of paraffin-type organic PCMs, is their low thermal conductivity value that leads to slower charging and discharging. Several strategies are applied[26]:

1. Metal fins or foams are embedded into the PCM layer
2. The addition of graphite or other carbon-based additives

3. The use of high-conductivity encapsulation materials These treatments may enhance the thermal conductivity by 3–10 times, which could significantly elevate the performance of SAH. 3.6 Criteria for PCM Selection In the selection of PCMs for three-pass solar air heater[27:]
4. The melting point of the PCM should be close to the desired outlet temperature.
5. The high latent heat capacity enables compact storage.
6. Cycling stability for maintaining performance in the long term.
7. Compatibility with the absorber plate and the materials of the enclosure.

3.7 Comparative Table of Common PCMs

Table 4: Common PCMs

PCM Type	Melting Temp (°C)	Latent Heat (kJ/kg)	Thermal Conductivity (W/m·K)	Typical Use
n-Octadecane	28–32	200	0.25	Low-temp drying
Stearic Acid	55–60	198	0.23	Industrial SAH
Na ₂ SO ₄ ·10H ₂ O	32–34	254	0.5	Medium-temp heating
CaCl ₂ ·6H ₂ O	29–32	190	0.6	Crop drying
Eutectic Mix	45–50	180–220	0.3–0.6	Tailored air heating

3.8 Advantages of PCM Integration in SAHs

1. Stabilizes outlet air temperature
2. Extends heating operation beyond sunlight hours
3. Reduces peak temperature fluctuations
4. Enhances overall daily thermal efficiency
5. Compatible with three-pass designs using fins, foams, or encapsulated layers

4. Integration of PCM in Three-Pass Solar Air Heaters

The incorporation of phase change materials (PCMs) in three-pass solar air heaters(3P-SAHs) appears to be an efficient method to improve the thermal performance, diminish temperature fluctuations, and prolong the operating time. By incorporating the multi-pass heat transfer effect with latent heat storage, the system can achieve stable outlet temperature under low solar irradiance or variable meteorological conditions[28 4.1 .[Objectives of PCM Integration The major goals of PCM inclusion in three pass SAHs are[29]: an improved thermal energy output.

1. Outlet air temperature stabilization.
2. Improved thermal efficiency of solar air heater.
3. Operation for more hours beyond the daylight.
4. Reduction of heat loss and enhancement of energy storage density. During solar peak periods, PCMs are heating when there is surplus solar energy and the heat is releasing slowly when solar intensity is lower. 4.2 Methods of PCM Integration There exist several methods to introduce PCMs into three-pass SAHs[30]:

Table 4: Several techniques are used to incorporate PCMs into three-pass SAHs

Method	Description	Advantages	Disadvantages
Macro-	PCM stored in tubes,	Simple, easy to	Large volume, lower

Encapsulation	containers, or panels in the airflow channel	maintain	surface area
Micro-Encapsulation	PCM enclosed in microcapsules dispersed in air channels or composite plates	High surface area, fast heat transfer	Costly, requires specialized fabrication
Shape-Stabilized PCM	PCM absorbed into porous or polymer matrices	Prevents leakage, enhances thermal conductivity	Moderate thermal conductivity, may require metal foams or additives
PCM-Fin Composite	PCM combined with metal fins for enhanced conduction	Improves charging/discharging rate	Slightly increases pressure drop

4.3 Typical Layouts of PCM in Three-Pass SAHs

PCMs are generally placed in the second or third pass of the solar air heater, where the air has gained some heat from the first pass but still requires additional energy. This placement allows the PCM to [31]:

Absorb excess heat during high solar irradiance • Release stored heat during evening or cloudy periods.

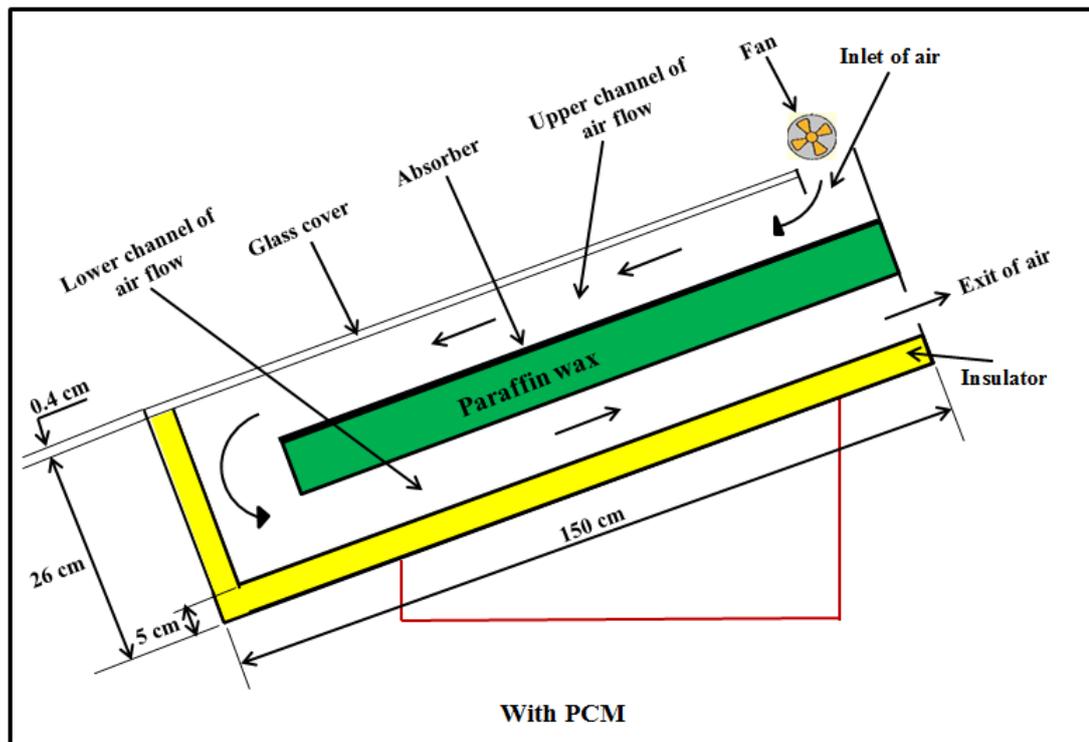


Figure 6: Textual Layout of PCM in Three-Pass SAH [31]

- ✓ PCM layer absorbs and stores latent heat in the second pass.
- ✓ During third pass and evening, the PCM releases heat, maintaining outlet air temperature.

4.4 Thermal Performance Enhancement

Integrating PCMs improves the thermal performance of three-pass SAHs in several ways: [32]

1. Outlet Air Temperature Stabilization

Table 5: Outlet Air Temperature Stabilization

Case	Max Temp (°C)	Min Temp (°C)	ΔT (°C)
------	---------------	---------------	-----------------

Without PCM	75	40	35
With PCM	70	55	15

Without PCM, outlet air shows large fluctuations. With PCM, temperature swings are reduced, providing consistent heating.

2. Daily Thermal Efficiency Improvement

$$\eta = \frac{Q_{\text{useful}}}{Q_{\text{incident}}}$$

Q_{useful} : Heat absorbed by air and PCM

Q_{incident} : Total solar radiation on absorber

Configuration	η_{daily} (%)
3-Pass SAH (No PCM)	55–60
3-Pass SAH + PCM	65–75

PCM integration increases energy utilization by storing heat that would otherwise be lost.

4.5 Enhancing Heat Transfer in PCM Layers

Low thermal conductivity of most PCMs can limit performance. Strategies include:

1. Fins inside PCM layer: Enhance conduction.
2. Metal foam or graphite matrices: Increase effective thermal conductivity.
3. Microencapsulation: Increases surface area and accelerates heat exchange.

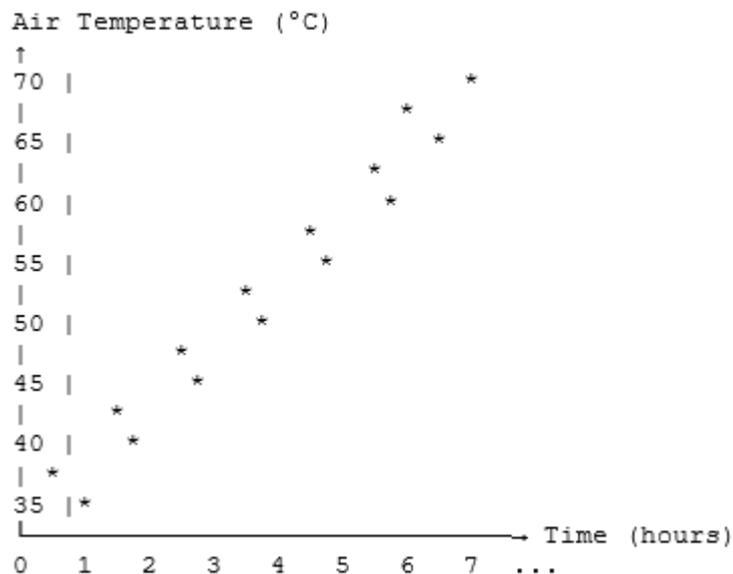


Figure 7: Air Temperature vs Time

PCM smooths air temperature profile, reducing peak and valley swings. Ensures stable heat supply for applications like drying or space heating.

4.6 Design Considerations for PCM Integration

Table 6: Design Considerations for PCM Integration

Parameter	Consideration
PCM Placement	Usually 2nd or 3rd pass for optimal charging/discharging
PCM Type	Match melting point with target air outlet temperature
PCM Volume	Sufficient to store excess energy without blocking airflow
Flow Rate	Moderate to allow heat transfer between air and PCM
Thermal	Can be enhanced with fins or composites

Conductivity	
Maintenance	Encapsulation to prevent leakage

5.1 Key Experimental Studies

Here is a summary of several representative experimental studies, their configurations, findings, and relevance for PCM-enhanced solar air heating systems[33].

Table 7: summary of several representative experimental studies, their configurations, findings, and relevance for PCM-enhanced solar air heating systems

Study (Authors, Year)	SAH Configuration	PCM Integration	Key Findings / Performance Gains
Ali, H. M. et al. (2015)	Double-pass solar air heater	Copper tubes filled with paraffin wax; some tubes also had aluminum or steel rods as thermal enhancers	<ul style="list-style-type: none"> - Using paraffin wax enabled useful heat delivery for ~1.5 hours after sunset. - With aluminum rods, the system supplied heat for ~2 hours after sunset. - Maximum instantaneous efficiency reached ~96% in optimized configuration.
Muhammad Sajawal et al. (2019)	Double-pass SAH with finned tubes	Finned tubes containing two types of PCM: RT44HC (higher melting point) in semi-circular finned tubes on upper pass; RT18HC (lower melting point) in circular finned tubes on lower pass	<ul style="list-style-type: none"> - The dual-PCM configuration (RT44HC + RT18HC) performed best. - Enhanced energy storage and more efficient charging-discharging compared to no-PCM and single-PCM configurations.
Abdulrahman S. Mahmood (2019)	Double-pass SAH	Rectangular cavity in the lower channel filled with paraffin wax	<ul style="list-style-type: none"> - After sunset, the outlet air temperature remained 1.5–6.5 °C above ambient for up to 5 hours due to PCM discharge. - Instantaneous thermal efficiency exceeded 100% during discharge (because of the released latent heat). - Daily efficiency improved: with PCM ≈ 56%, without PCM ≈ 47%.
Experimental Study in Tikrit Journal (2023)	Single / multi-pass SAH? (or SAH-storage hybrid)	Paraffin wax located under the absorber plate	<ul style="list-style-type: none"> - Reported a 12% gain in daily efficiency when PCM was used compared to the same system without PCM.
Haijun Han et al. (2022)	Solar heating system (building, radiator + collector)	Inorganic salt-based PCM (calcium-chloride–ammonium chloride with nucleating agent) integrated in radiators / heat storage	<ul style="list-style-type: none"> - The PCM-based system stabilized room temperature over a heating period, keeping test rooms on average 4.6 °C warmer than control rooms without PCM. - Energy saving of about 45% during the heating season

			compared to non-PCM reference.
Balakrishnan et al. (2022)	Solar air heater (pass not explicitly PCM double-pass studied)	PCM layer integrated (paraffin) plus finned plates (or similar)	- Night-time air temperature boost of ~7.5 °C in a greenhouse model due to PCM. - Thermal efficiency increase by ~18%.

5.2 Analysis of Experimental Results

From those works, a couple of patterns and implications could be drawn out[34.1 :[HEATING TIME IS THE LONGEST IN THE PCM DISCHARGE In Mahmood’s double-pass SAH, the paraffin PCM continued to release the stored energy for a number of hours after sunset and kept the air at a high temperature. Ali et al. have demonstrated that the inclusion of thermal enhancers within the tubes of PCM (such as aluminum rods) prolongs even the period of discharging energy.2 .Improved Efficiency Overall daily efficiencies have increased clearly for the PCM-based systems ;Mahmood’s heater got ~56% with PCM vs 47% without PCM .In the experiments Tikrit Journal, the use of PCM achieved an absolute efficiency gain of approximately 12% .In some cases, instantaneous efficiency even exceeded 100% during PCM discharge, since latent heat is “free” once stored.3 .Thermal Conductivity Enhancers Are Better in Performance Using finned tubes and two types of PCMs (with distinct melting points) had a positive effect on charge and discharge processes in Sajawal et al.’s work. Ali et al. proved that the addition of metallic rods (either aluminum or steel) into the PCM-filled tubes is advantageous because it increases the internal heat transfer.4 .Thermal stability of temperature The work by Haijun Han et al. showed that when a PCM is incorporated in a building heating system, a more stable indoor temperature with less indoor temperature under- or overheating and a better thermal comfort over the period can be achieved. Balakrishnan et al., demonstrated that it is possible for PCM to retain warmer air over night in a greenhouse raising the total heat delivery..

6. Conclusion

Three-pass SAHSs filled with latent heat storage materials can offer an attractive alternative for enhancing the thermal performance and stability of SAHSs. PCMs help in improving temperature uniformity, operating hours and system efficiency. Paraffin-based PCM makes the majority of applications, but the conductivity-enhanced and composite PCMs demonstrate better characteristics. Experimental and numerical results prove that multi-pass flow arrangements with PCM storage yield significant efficiency improvements. Future research should be directed towards novel PCM composites, better encapsulation, integrated hybrid systems and large-scale demonstrators in the line with the objective set in order to fully exploit the potential of these systems.

Reference

1. H. A. Maarof, “CFD modeling of a tubular three-pass solar air heater with phase change material (PCM): Investigating heat-transfer enhancement and energy efficiency”, *Journal of Energy Storage*, 2024.
2. H. A. Maarof, “Comparative analysis of tubular three-pass SAH with PCM vs conventional SAH”, *J. Energy Storage*, 2024
3. A. Hedau & S. Singal, “Study on the thermal performance of double-pass solar air heater with PCM-based thermal energy storage system”, *J. Energy Storage*, 2023.

4. HS Dheyab, M. S. Al-Jethelah, T. K. Ibrahim, et al., “Closed Solar Air Heater System Integrated with PCM”, *Tikrit Journal of Engineering Sciences*, 2023.
5. Xinran Wang, Yanhua Diao, Zhen Wang, Tingting Zhu, “Experimental thermal performance of a solar air heater with rectangular fins and phase change material”, *Applied Thermal Engineering*, 2024.
6. Z. N. Suzah, “Performance Enhancement of Double-Pass Solar Air Heater with PCM”, *Journal of Engineering and Applied Scientific Development*, 2025.
7. Ismail Ata, Yunus Erkam Özselçuk, “Effect of Phase-Change Materials in the Performance of a Solar Air Heater”, research-gate / preprint, ~2025.
8. Abhishek Rai, N. S. Thakur, Deepak Sharma, “Numerical Simulation of Thermal Energy Storage using Phase Change Material”, arXiv, 2023. Michael Shanks, Uduak Inyang-Udoh, Neera Jain, “Design and validation of a state-dependent Riccati equation filter for state of charge estimation in a latent thermal storage device”, arXiv, 2023.
9. Poongavanam Ganeshkumar, Vigneswaran Shunmugharajan, P. Murugan & Ramkumar Vanaraj, “Exploring the thermal performance of a solar air heater with a V-corrugated and shot-blasted absorber plate comprising nano-enhanced phase change materials”, *Energy*, 2024
10. P. Balakrishnan, Senthil Kumar Vishnu, Jayaraman Muthukumaran et al., “Experimental thermal performance of a solar air heater with rectangular fins and phase-change material”, *Journal of Energy Storage*, 2024.
11. Preprint: “Performance Improvement of a Solar Assisted Absorption Cooling System Integrated with Latent Heat Thermal Energy Storage”, Preprints.org, 2023
12. Farhan Lafta Rashid, Mudhar A. Al-Obaidi, Anmar Dulaimi, Haitham Y. Bahlol, Ala Hasan, “Recent Advances, Development, and Impact of Using Phase Change Materials as Thermal Energy Storage in Different Solar Energy Systems: A Review”, *Designs*, 2023.
13. Jianjun Hu, Shuhan Lan, Jingheng Hu, “A self-driven solar air heater integrated with a thermal energy storage unit: Design and experiment study”, *Energy*, 2023.
14. Hu Wentao, Vladimir N. Alekhin, Yang Du, Chaoping Hou, “Design and thermal performance evaluation of the thermal storage layer of a solar air collector with comprehensive consideration of six factors of phase-change materials”, *Renewable Energy*, 2024.
15. Houssam Eddine Abdellatif, Shan Ali Khan, Nahid Fatima, Abdullah Alhushaybari, “Enhancing Latent Heat Storage: Impact of Geometric Modifications, S-shaped enclosure Walls, and L-shaped fins”, *Journal of Thermal Analysis and Calorimetry*, 2025.
16. J. F. Hinojosa, S. Moreno, Victor Maytorena, “Low-Temperature Applications of Phase Change Materials for Energy Storage: A Descriptive Review”, 2023.
17. Tauseef-Ur-Rehman, Dang Dinh Nguyen, Sajawal Muhammad, “Smart optimization and investigation of a PCMs-filled helical finned-tubes double-pass solar air heater: An experimental data-driven deep learning approach”, *Solar Energy*, 2024.
18. Sudhir Kumar Pathak, Vineet Tyagi, K. Chopra, Zhenjun Ma, “Energy, exergy, economic and environmental analyses of solar air heating systems with and without thermal energy storage for sustainable development”, *Renewable Energy*, 2023.
19. T. A. Rizal, et al., “Integration of Phase Change Material in the Design of a Cylindrical Through Collector for Latent Heat Storage”, *Entropy*, 2021 :
20. N. Van Hap, et al., “Numerical and experimental investigation of the solar air collector with phase change material,” *Scientific Reports*, 2025

21. I. Ata, "Experimental analysis of a phase change material (PCM) in solar air heaters," *ScienceDirect*, 2025.
22. S. L. Sharma, "Advancement in solar air heater with integrated PCM-storage: A review," *International Journal of Energy Research*, 2024.
23. Deepak Kumar S. Jani, "Design and performance analysis of a solar air heater with PCM heat storage for residential applications," *International Journal of Innovative Research in Engineering and Management (IJIREM)*, 2023.
24. Y. Ma, "Experimental analysis of a solar-driven modular latent-heat thermal energy storage system for ventilation air heating," *Applied Thermal Engineering*, 2025
25. W. A. Qureshi, N. K. C. Nair, M. M. Farid, "Experimental investigation of solar air heater using pin-fin absorber plate immersed in paraffin wax PCM," *International Renewable Energy Magazine*, 2023
26. H. S. Dheyab, M. Al-Jethelah, Thamir K. Ibrahim, "Closed solar air heater system integrated with PCM (RT42, RT50) in a finned heat-exchanger unit," *Tikrit Journal of Engineering Sciences*, 2023.
27. P. Liu, J. Zhao, J. Chen, "Simulation study of a novel solar air-source heat pump heating system based on phase-change heat storage," *Sustainability*, 2023
28. Y. Hu & P. Heiselberg, "Thermal performance of a ventilated solar collector with PCM-filled fins in the ventilation cavity," *AIVC Conference Paper*, 2023
29. Yuxuan Deng, Xiaojuan Zhu, Yanna Li, Jing Xu, "Impact of solar-driven heating strategies on the phase-change thermal storage performance of erythritol," *Frontiers in Chemistry*, 2024.
30. Sadeghi, et al., "Recent advances, development, and impact of using PCMs as thermal energy storage in different solar energy systems: A review," *Designs*, 2023
31. Qiong Ye, L. Ba, G. T. M. Nguyen, R. Absi, "Experimental and numerical simulation study on the thermal performance of building envelope structures incorporating solid-solid PCM," *arXiv preprint*, 2025.
32. Inderpreet Singh, Vikrant Khullar, "Predicted performance bounds of thermochromism-assisted photon transport for efficient solar thermal energy storage with PCM," *arXiv preprint*, 2023.
33. Diego R. Rivera, Ernesto Castillo, Felipe Galarce, Douglas R. Q. Pacheco, "Improving performance estimation of a PCM-integrated solar chimney through reduced-order data assimilation," *arXiv preprint*, 2025.
34. Sajawal M., Rehman T., Ali H. M., Raza A., Bhatti M. S., "Applications of encapsulated phase change materials for solar air heaters: experimental study with double-pass SAH," *Journal of Energy Storage*, 2024. (From detailed survey in recent review)