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*Research Article*

# Computational Fluid Dynamics Analysis of a Solar Dryer with Various Phase Change Materials

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**Abstract**

A phase change material (PCM) is an organic (or inorganic) chemical that may store and release thermal energy in latent form as it changes physical states. This investigation aims to see how phase transition materials influence the thermal efficiency of the solar dryer. For the performance analysis, three PCMs were used: paraffin wax, lauric acid, and palmitic acid. As drying material, 5 mm thick potato slices were employed. According to the computational results, the total input thermal energy for the dryer for paraffin wax, lauric acid, and palmitic acid was about 17.36 MJ, 18.46 MJ, and 17.76 MJ, respectively, for 2 kg drying mass. When paraffin wax, lauric acid, and palmitic acid were utilized, the overall efficiency of the dryer increased by about 87%, 40.2%, and 12.4%, respectively, compared to the conventional dryer. By comparing the results of simulations and predictions, it is concluded that paraffin wax is the best-performing PCM for solar dryers as the energy storage material.

***Keywords:*** *Computational fluid dynamics; heat transfer; lauric acid; palmitic acid; paraffin wax; phase change materials.*

## 1. Introduction

Since ages, food and agricultural harvests have been dried under the sun. On the other side, this procedure is troubled with issues, such as items hampered by weather conditions, including rain, wind, humidity, birds and dust. Besides this, the method is labor-intensive, time-consuming, and necessitates extensive product dispersion to dry. The alternative ways of drying those products using heat from electricity or burning biomass are expensive and not environmentally friendly. In this situation, solar drying can be applied. Small food processing businesses may employ solar dryer technology to create nutritious, premium food products. As per National Horticulture Database (3rd Advance Estimates) published by National Horticulture Board, during 2021-22, India produced 107.24 million metric tons of fruits and 204.84 million metric tons of vegetables [1-3].

Significant moisture levels may be found in various fruits and vegetables. The food sector uses high-tech drying apparatus, including ice cream, drum, and steam dryers, which control the market for food goods. Such dryers have a high market value. Thus, only substantial businesses can afford them. Most small-scale grocery businesses that work with the farmer cannot pay for the pricing owing to the hefty start-up expenses. As a result, such companies and farmers have started to favor low-cost and simple drying solutions. For thousands of years, farming and other foodstuffs have been dried in sunlight & air outside. In several developing nations, solar dryers are one of the most effective and efficient methods to use energy from the sun for drying and space heating. Solar dryers in emerging markets are widely used for drying tobacco, tea, jaggery, coffee, grammes, grapes and spices [4-6].

Herbal and spice products are commonly dried in several South East Asian nations. However, because of weather circumstances, the application of sunlight for drying is restricted owing to loss due to the body’s reaction on unpredictable wet days. It has been found that prolonged contact of agricultural goods with the sunlight on hot days might cause hardening. Hardening occurs without the use of crop goods. It traps humidity within the exterior layer, causing crops to be spoiled. For these reasons, solar drying emerges as a novel method for its preservation [7-9].

## 2. Literature Review

Lower thermal efficiency is the primary reason behind the unpopularity of solar drying in society. Hence, some arrangement is necessary to improve the solar dryer's thermal performance. Therefore, a literature review was conducted to understand methods for improving the thermal efficiency of solar dryers.

Hii et al., [1] showed that solar drying (placing the crops beneath direct sunlight) was feasible; however, the product obtained was of inferior quality due to contamination because of dirt, bugs, winged animals, dogs, and even precipitation. Furthermore, direct exposure to bright beams caused a depletion of vitamins and nutrients, dietary supplements, and have taken a long time to dry out.

Umogbai et al., [2] investigated the difference between solar drying and sunlight-based drying. They discovered that sunlight-based dryers produce greater temperatures, lesser relative humidity, less product wetness, and lesser

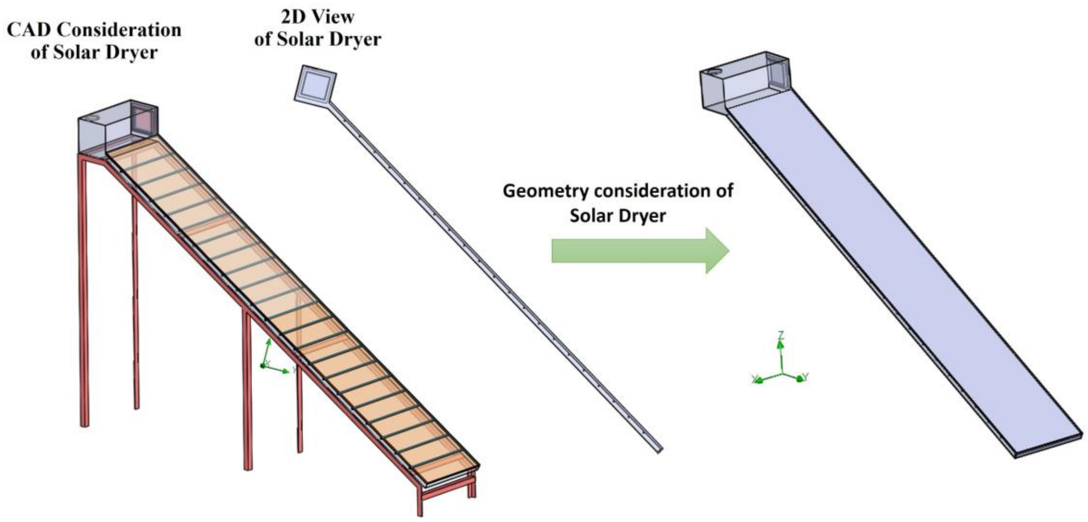



*Figure 1. CAD modelling of solar dryer.*

degradation throughout the drying process. Rajeshwari and Ramalingam [10] showed that when sun-oriented dryers were used instead of outdoor drying, drying time was reduced by roughly 20%, while the dried products were of a more excellent standard.

Some of the publications on tunnel dryers, halfway and half dryers and even, vertical dryers, multiple-pass dryers, and dynamically detached dryers are all investigated in various sizes and designs. They came up with common conclusions that their systems were energy efficient and will effective for drying applications [11-18].

The effectiveness of an indirectly conduction-driven solar chilly dryer paired with a thermal storage material was constructed by Megha S. Sontakke and Sanjay P. Salve [19]. The chilies were dried in the bottom and upper containers, ranging from a starting humidity level of 72.8% to ending humidity levels of 9.2% and 9.7% (wet premise), respectively.

Toshniwal et al., [20] demonstrated the design and construction of a direct natural convection sun drier for drying tapioca in remote places. The study showed that an entire batch of 100 kg of cassava had been dried in 20 hours (2-day drying cycle), which requires a solar panel with a minimum size of 7.56 m2. Seemingly, 79% and 10% moist basis were the first and ultimate moisture content rates. Given a peak everyday total radiation level from the sun on the ground's surface of 13 MJ/m2/day, the typical surroundings are $32^0$C air temperature and 74% relative humidity [21-22].

The primary goal of the current research is to maximize the efficiency of the solar dryer during off-sunshine hours Using ANSYS flow simulation software, every aspect of assessment was completed.

The novelty of this research is that PCM tubes were kept horizontally at the bottom of the absorber copper plate instead of vertically at the top of the absorber copper plate, which was generally found in the literature.

## 3. Methodology

The various steps used to conduct the analysis were as follows:

a) Design of solar dryer equipped with PCM.
b) Finalize the dimensions.
c) Drawing in Catia V5 software.
d) CFD simulations
e) Analyzing the results.

SolidWorks flow simulation V-2020 was used to analyses the solar dryer. The computations were necessary to design the model to investigate the interaction of liquids and gases with the surfaces determined by boundary conditions. Software enhanced the precision and speed of complicated modelling situations, including turbulent flows, as the result of continuing studies.

### 3.1 Design Model

SolidWorks structures from the analysis system have been selected; then, the properties of the materials have been added from engineering data or material library. The material chosen for analysis was copper plate mounted on mild steel as the base part, clear glass, which produced a greenhouse effect and paraffin wax, lauric acid and palmitic acid for energy storage. The 3-dimensional sketch was designed in geometry and open design modeler. Figure 1 shows the 3D structure of a solar dryer.

A CAD model based on the phase change characteristics of several materials was developed to conduct a CFD analysis of the solar dryer. The solar dryer has two parts, mainly duct and drying cabinet. The air channel consists of glass, copper absorber plate and copper tubes filled with PCM. On the other hand, the drying cabinet where materials to be dried located, consists of shelves and exhaust fan used to intake the air from the atmosphere through the duct channel and the drying cabinet.

The function of air heaters is to heat the air. Therefore, the hot air from the atmosphere enters the duct bottom area, which releases heat to the PCM tubes and furthers the air exhaust through the drying cabinet. Hence, in this way, PCM materials store heat from the hot air and release it during off-sunshine hours for drying. Palmitic acid, lauric acid, and paraffin wax were the investigated materials. They were placed in copper tubes on the underside of the absorber copper plate.

Properties of several materials used in the construction of solar dryer are depicted in Table 1.

The absorber tubes have been modelled for the material's types and boundary conditions. According to the fluid condition (hydraulic diameter and fluid velocity), turbulence conditions are applied for investigation. The mesh size in this analysis is kept at standard state. The properties of PCMs used are listed in Table 2.

*Table 1. Properties of solid materials used in a solar dryer.*

| Material | Density ($Kg/m^3$) | Specific heat (J/kgK) | Thermal conductivity (W/mK) |
|---|---|---|---|
| Copper | 8954 | 383 | 386 |
| Mild Steel | 7680 | 445 | 45 |
| Glass | 2500 | 670 | 0.7443 |

*Table 2. Characteristics of the specified materials.*

| SN | Thermo-physical properties | Units | PCM Material | | |
|---|---|---|---|---|---|
| | | | Palmitic Acid | Lauric Acid | Paraffin Wax |
| 1 | Density | $kg/m^3$ | 860 | 880 | 900 |
| 2 | Specific heat | kJ/kg K | 2.4 | 2.3 | 2.5 |
| 3 | Thermal conductivity | W/m K | 0.2 | 0.18 | 0.23 |
| 4 | Latent heat of fusion | kJ/kg | 200 | 230 | 220 |
| 5 | Melting temperature | °C | 63 | 44 | 60 |

As seen in Table 2, lauric acid has a higher latent heat of fusion than palmitic acid and paraffin wax. In contrast, paraffin wax has a far higher density, specific heat, and thermal conductivity.

### 3.2 Boundary Conditions

The air input velocity is 1 m/sec at the atmospheric temperature of 25°C; the solar irradiation intensity is observed to be 733 $W/m^2$. The following Table 3 lists all boundary conditions.

Table 3. Boundary conditions of the Model.

| Boundary conditions | | |
|---|---|---|
| *Parameters* | *Units* | *values* |
| Solar Irradiation | W/m² | 733 |
| *Inlet air conditions:* | | |
| Temperature | °C | 25 |
| Humidity | % | 50 |
| Velocity | m/s | 1 |
| Ambient material temp | °C | 25 |
| *Outlet air conditions* | | |
| Temperature | °C | 52 |
| Humidity | % | 76 |
| Pressure | bar | 1.01325 |

### 3.3 Heat Transfer Rate

In a given system, heat transfer is the movement of heat across the system's boundaries due to a temperature difference between the system and its surroundings. As a result, it is an indicator of the particle's kinetic energy when there is a difference in temperature between a hot and cold body (or bodies). For a particular system, the rate of heat transfer relies on the mass (m) of the system, the specific heat capacity (c), and the temperature differential (ΔT) between the hot and cold bodies. As a result, the sensible heat transfer equation is as follows:

$$Q = mc\Delta T \tag{1}$$

However, the heat transfer rate is governed by the well-known three modes of heat transfer. They are described as below:

i) Heat transfer by conduction is the process of transmitting energy from one medium particle to another when the particles are in touch with each other.

$$Q = \frac{kA(T_{hot}-T_{cold})}{d} \tag{2}$$

This is called Fourier's law of heat conduction.

ii) Heat transfer by convection is described as the movement of fluid molecules from higher to lower temperature zones.

$$Q = hA(T_{hot} - T_{cold}) \tag{3}$$

The equation 3 is called Newton's law of cooling.

iii) Heat transfer by radiation refers to thermal radiation. The emission of electromagnetic waves produces thermal radiation. These waves carry away the energy from the producing body. Radiation is transmitted via a vacuum or a transparent material, whether solid or liquid. Thermal radiation is caused by the random movement of molecules in materials. The movement of charged electrons and protons causes the emission of electromagnetic radiation.

$$Q = \in \sigma A(T_{Hot}^4 - T_{Cold}^4) \tag{4}$$

This equation is called Stefen Boltzmann's law.

## 4. Results & Discussions

This section illustrates the computational results obtained and its consequences on the performance of solar dryer.

### 4.1 Temperature Distribution for Different PCM

Figures 2 (2a, 2b, 2c) and 3 (3a, 3b, 3c) show the temperature distribution of lauric acid, palmitic acid and paraffin wax in the duct area. Nevertheless, Figure 4 (4a, 4b, 4c) shows that the temperature distribution of paraffin wax in the drying cabinet is satisfactorily greater than lauric acid and palmitic acid, respectively, because paraffin wax has higher thermal conductivity and specific heat than the other two.

### 4.2 Air Flow Velocity Contours Inside Chambers

Figures 5 (5a, 5b, 5c) and 6 (6a, 6b, 6c) show the airflow velocity contours inside the whole system and only inside the drying cabinet. It illustrated that although the air flow velocity is constant for all the three cases; the outlet temperature of air coming from duct fitted with paraffin wax has highest temperature as compared to other PCMs. The reason behind this is the superior thermo-physical properties of paraffin wax.

### 4.3 Temperature Distribution of Air

Figure 7 shows that the air temperature distribution in the entire system is better in paraffin wax compared to lauric acid and palmitic acid because it has high density and high thermal conductivity compared to the other two.

### 4.4 Temperature Distribution of Air at Chamber

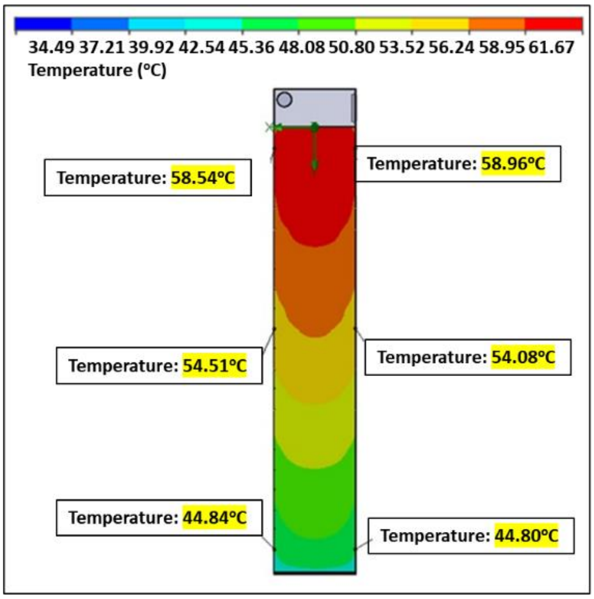
Temperature analysis of air on the fluid at the drying chamber for lauric acid was an average of 530C, while in the case of palmitic acid, it was 51.20C and for paraffin wax, it was 56.30C as shown in figure 8.

### 4.5 Model Analysis

Overall airflow and temperature distribution results clearly show the results in comparison between all three materials for PCM during the experiment in the solar dryer in CFD. Air temperature at the exhaust surface is shown in

Figure 9., where the Y axis denotes the change in temperature at 0° C. In contrast, the X axis indicates lauric acid, paraffin wax and palmitic acid. It has been concluded that paraffin wax has a much better temperature rise, as shown in Figure 9.

Heat transfer rate from paraffin wax has higher as compared to lauric acid and palmitic acid, respectively, shown in Figure 10.

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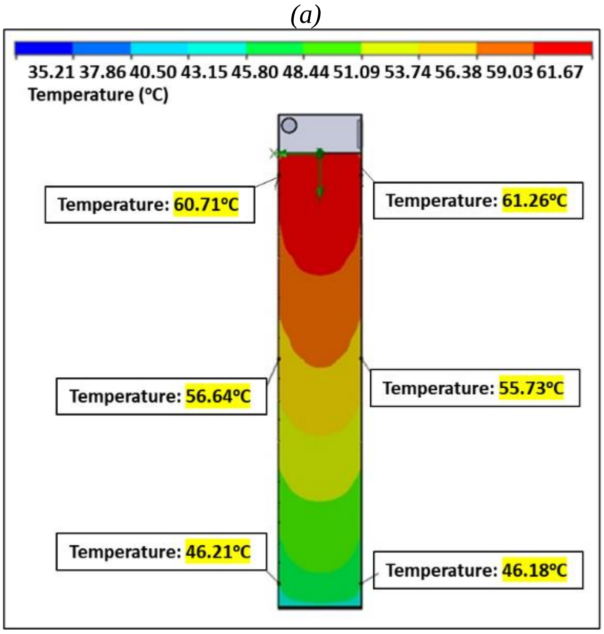


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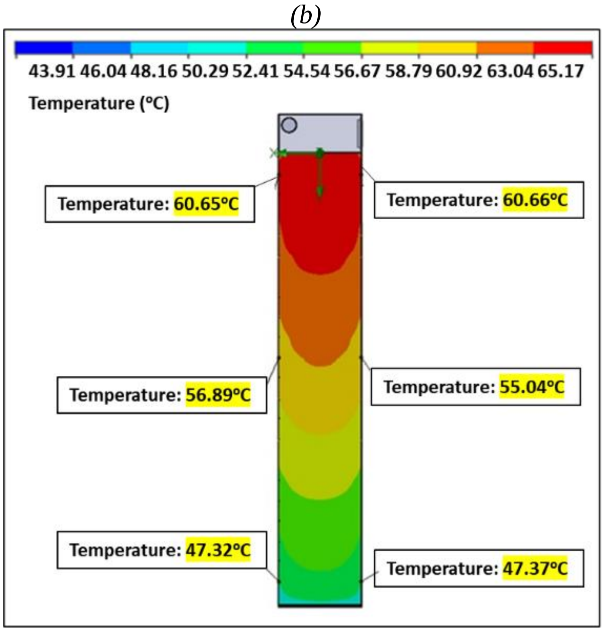


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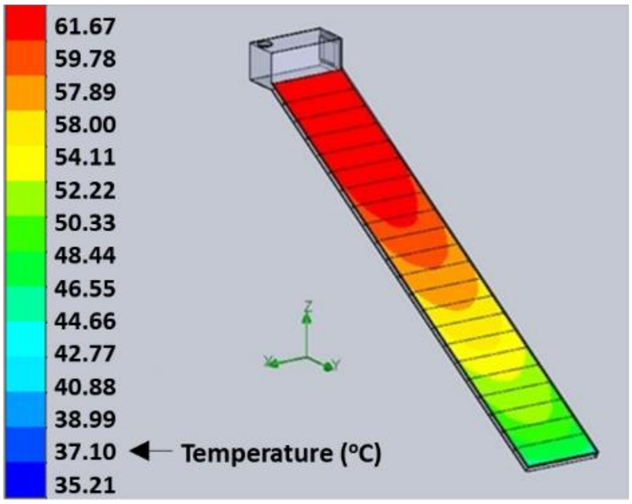
*Figure 2. Temperature distribution of Copper Plate of Solar Dryer (Top View) in (a) Palmitic acid, (b) Lauric acid, (c) Paraffin.*

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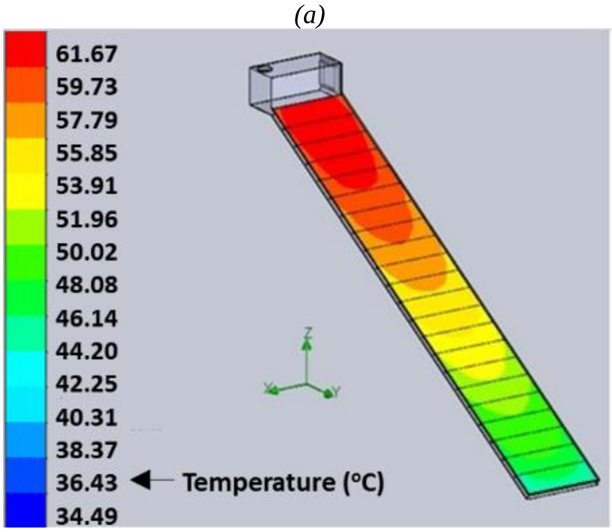


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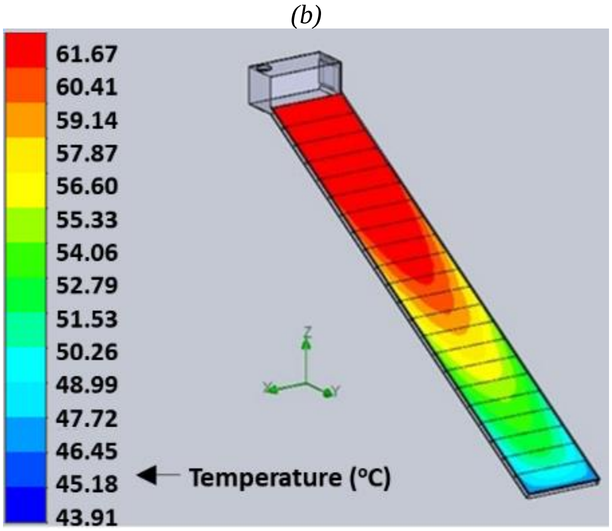


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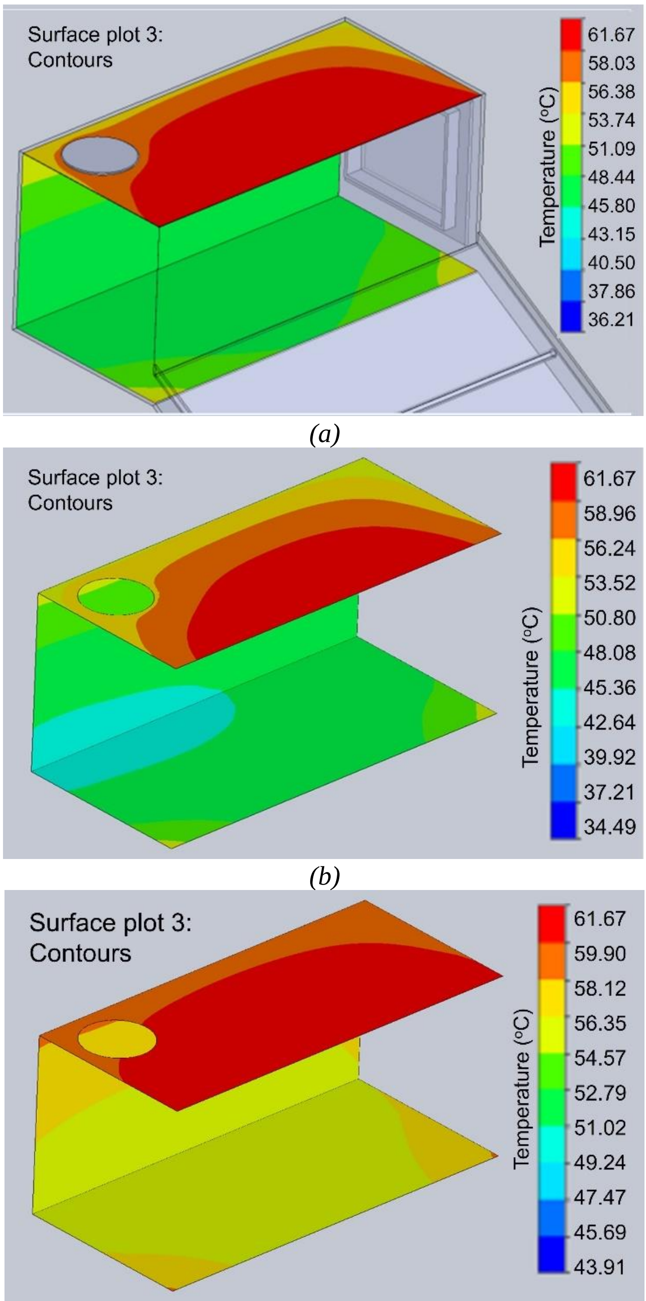
*Figure 3. Temperature Distribution (Schematic View) in (a) Lauric acid (b) Palmitic acid & (c) Paraffin wax.*




*(a)*

*(b)*

*(c)*

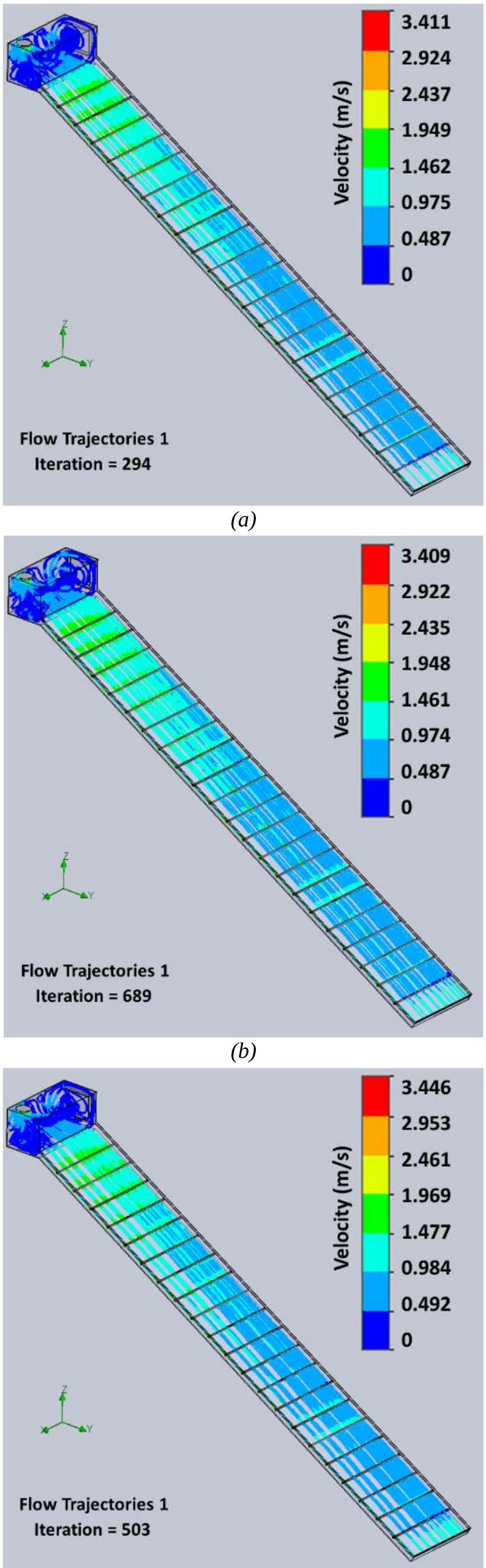
*Figure 4. Temperature distribution in drying cabinet in (a) lauric acid (b) palmitic acid (c) paraffin wax.*

The heat transfer rate observed during analysis is represented by the Figure 10. It shows that the heat transfer rate of the paraffin wax is 252W, much more significant than lauric acid having 225W and palmitic acid having 210W, since paraffin wax has higher thermal conductivity, specific heat and density.

## 5. Conclusion

The present research investigates the best-performing PCM for solar dryers and air heaters. The three distinct PCMs, palmitic acid, lauric acid and paraffin wax, were analyzed using the latest simulation technology. From this investigation, the following conclusions are drawn:

According to the computational analysis, the dryer needed about 17.36 MJ, 18.46 MJ, and 17.76 MJ of heat energy to dry 2 kg of potatoes using paraffin wax, lauric acid, and palmitic acid.




*(a)*

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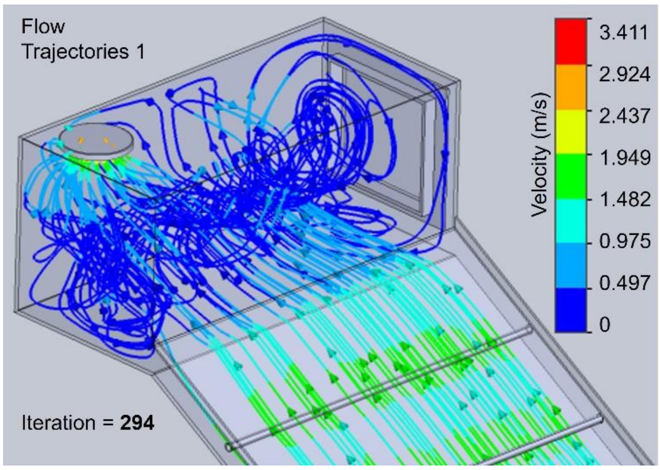
*Figure 5. Air flow velocity contours (Top View) in (a) palmitic acid, (b) lauric acid, (c) paraffin wax.*

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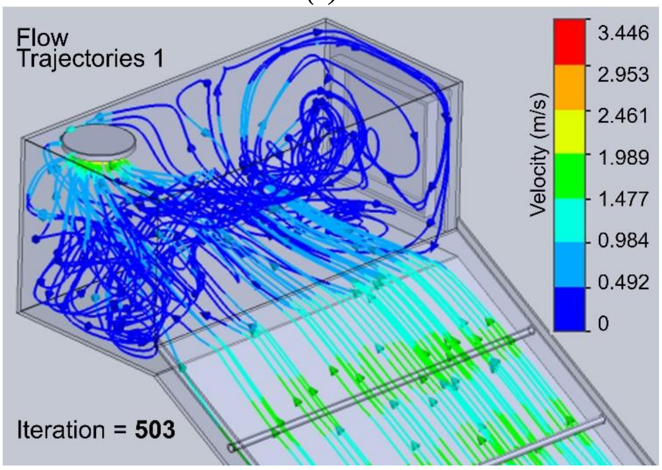


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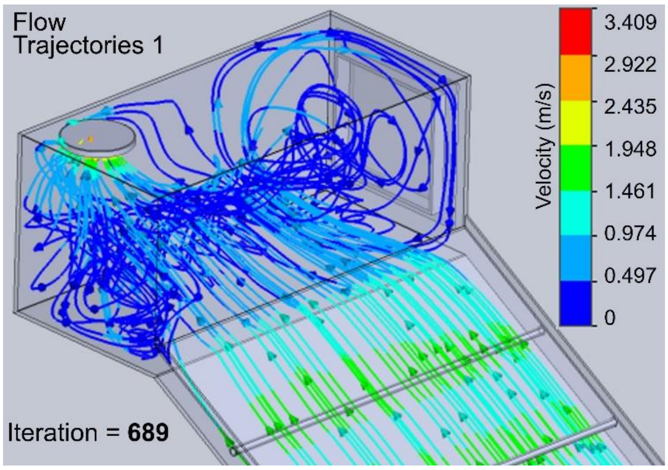



*(c)*

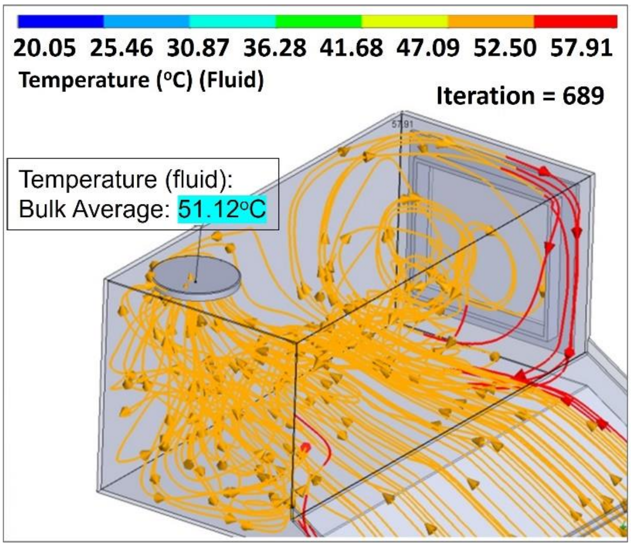
*Figure 6. Air flow velocity contours inside the chamber for (a) palmitic acid, (b) lauric acid (c) paraffin wax*

When paraffin wax, lauric acid, and palmitic acid were used, the dryer was 87%, 40.2%, and 12.4% more efficient than a traditional dryer.

Paraffin wax absorbs and transmits heat faster than lauric acid and palmitic acid.

Hence, paraffin wax emerged as the best-performing phase change material for solar dryers as the energy storage system.

These research findings are helpful for researchers and industry personnel in designing effective heat storage systems to reduce heat loss from solar dryers and solar air heaters. In future, multi-objective optimization and thermo-economic analysis will be required to estimate the precise quantity of PCM for further investigations.

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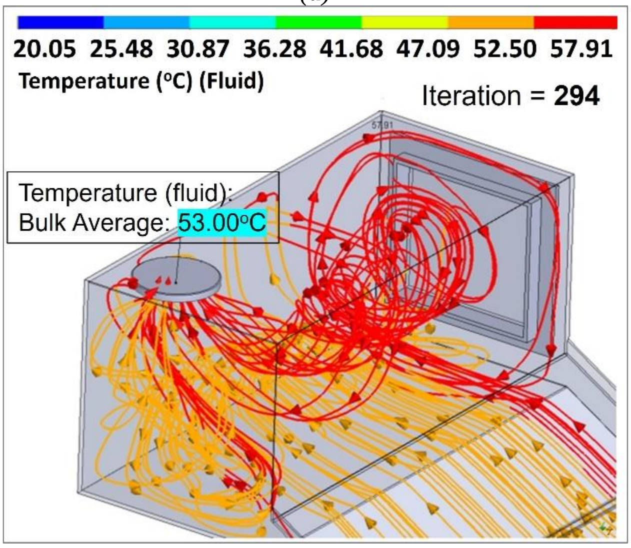


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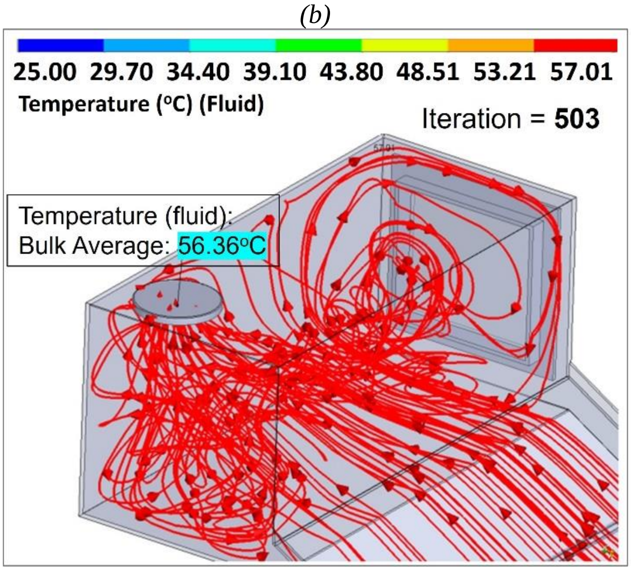


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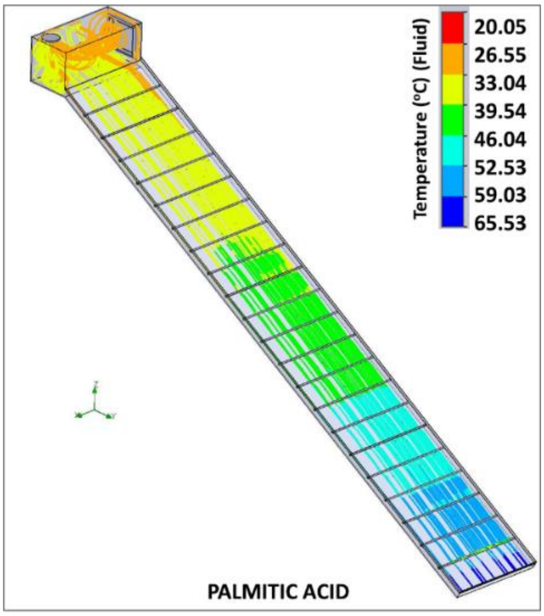
*Figure 7. Temperature distribution of air at chambers for lauric acid, palmitic acid and paraffin wax respectively in (a) palmitic acid, (b) lauric acid, (c) paraffin wax.*

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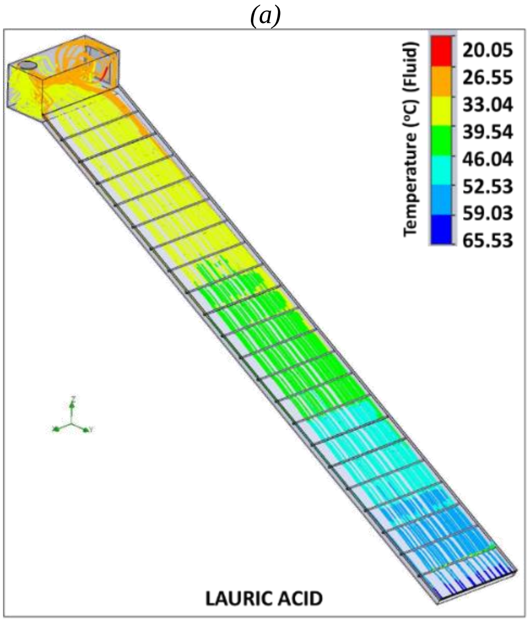


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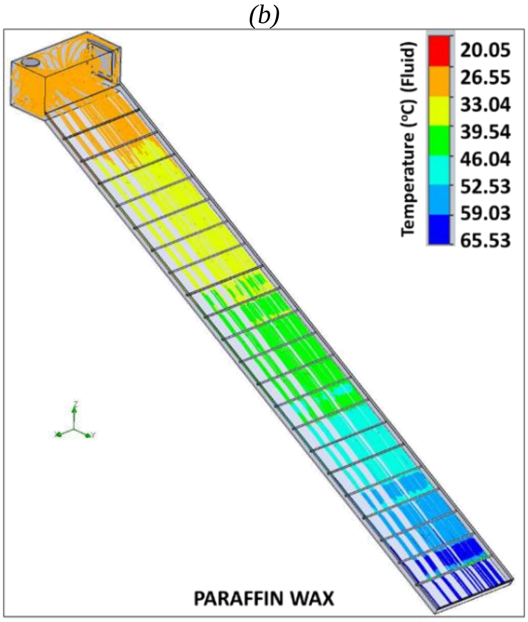


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*Figure 8. Temperature distribution of air (top view) in (a) palmitic acid, (b) lauric acid (c) paraffin wax.*

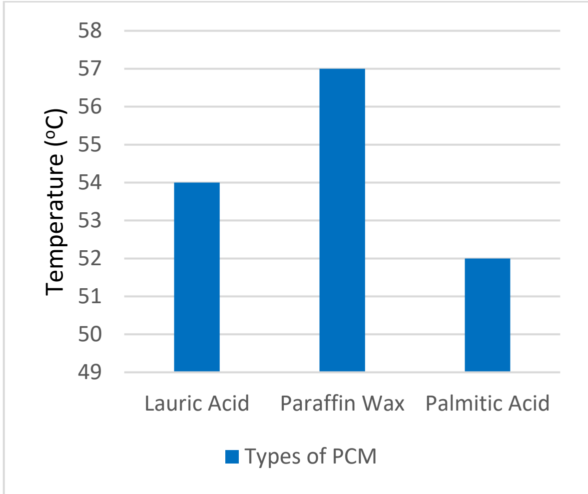


*Figure 2. Air Temperature at the exhaust surface of the drying cabinet.*

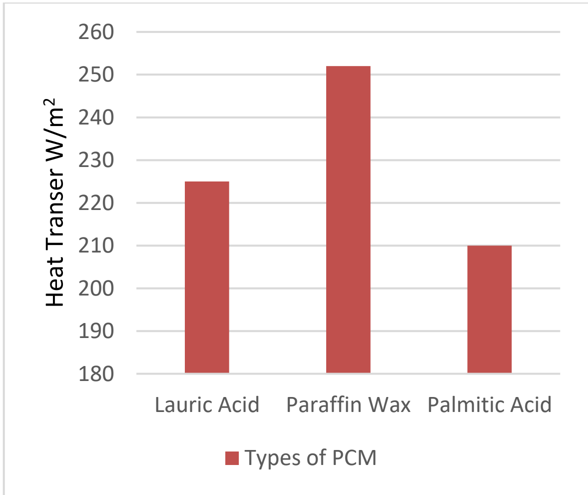


*Figure 3.Heat transfer rate for PCMs.*

## Nomenclature

| | |
|---|---|
| $A$ | Surface area (m$^2$) |
| $C$ | Specific heat capacity (J/kg K) |
| $d$ | Thickness of copper plate (m) |
| $h$ | Heat transfer coefficient (W/m$^2$ K) |
| $k$ | Thermal conductivity (W/m K) |
| $m$ | Mass (kg) |
| $Q$ | Heat transfer rate (W/m$^2$) |
| $T$ | Temperature ($^0$C) |
| $T_{cold}$ | Cold (fluid) temperature ($^0$C) |
| $T_{hot}$ | Hot (surface) temperature ($^0$C) |
| $\sigma$ | Stefan Boltzmann constant (W/m$^2$ K$^4$) |
| $\in$ | Emissivity |

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