

# A PERFORMANCE STUDY OF DEHUMIDIFICATION IN AN EVAPORATIVE COOLING SYSTEM USING THERMOSYPHON HEAT PIPES

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**ABSTRACT:** This study investigates the performance enhancement of an evaporative cooling system by integrating thermosyphon heat pipes to improve dehumidification efficiency in hot and humid climates. The experimental setup comprised a thermally insulated cubic test chamber ( $100 \times 100 \times 100 \text{ cm}^3$ ) fitted with a cellulose-based cooling pad, axial flow fans, and five copper heat pipes (9.5 mm in diameter and 40 cm in length) charged with R-134a refrigerant. The heat pipes were positioned upstream of the cooling pad to passively extract latent heat and reduce moisture content in the incoming air prior to evaporative cooling. Experiments were conducted under two levels of natural solar radiation, averaging approximately  $600 \text{ W/m}^2$  and  $750 \text{ W/m}^2$ , respectively, recorded using a pyranometer at 30-minute intervals. Measured parameters included dry-bulb temperature and relative humidity, collected using calibrated K-type thermocouples and digital hygrometers. The results indicate that the heat pipe system effectively reduced the relative humidity of supply air by approximately 6% to 10%, with maximum reductions reaching 12.5% under high solar intensity. This pre-conditioning process not only lowered the latent cooling load but also enhanced overall cooling performance. While the dry-bulb temperature increased slightly, thermal comfort improved significantly. The findings highlight the potential of this passive hybrid approach to enhance indoor environmental quality and energy efficiency in tropical buildings. Future work should focus on airflow optimization and the use of alternative refrigerants to refine system applicability in real-world scenarios.

*Keywords: Heat Pipe, Evaporative Cooling, Dehumidification, Energy Efficiency, Tropical Climate*

## 1. INTRODUCTION

In tropical countries such as Thailand, where annual temperatures commonly range between  $32^\circ\text{C}$  and  $35^\circ\text{C}$  and relative humidity often exceeds 70%, the pursuit of indoor thermal comfort results in significant energy consumption, particularly from air-conditioning systems. Conventional vapor-compression air conditioners not only demand substantial electrical energy but also utilize refrigerants with high global warming potential, contributing to both ozone depletion and climate change [1–3]. These environmental concerns have intensified the search for alternative, energy-efficient cooling technologies that can operate effectively in hot and humid climates.

Evaporative cooling systems have attracted considerable interest because of their low energy requirements and simple operating principles. By utilizing the latent heat of water evaporation to reduce air temperature, these systems perform well in dry and semi-arid regions. However, their effectiveness is limited in humid environments such as Southeast Asia, where the ambient air frequently approaches saturation. Under these conditions, the reduced dry-bulb to wet-bulb temperature difference restricts the achievable cooling capacity [4–5]. As a result, hybrid cooling configurations that integrate passive and

active dehumidification techniques have been increasingly explored to improve system performance.

Among various passive heat-transfer devices, thermosyphon heat pipes have gained prominence because of their ability to transfer heat efficiently without mechanical components. These devices can remove latent heat by condensing moisture on a cooled surface, thereby lowering humidity before the air enters the evaporative cooling stage. Previous studies have demonstrated the potential of incorporating heat pipes into HVAC and agricultural applications. Van Den Bulck et al. reported the use of rotary heat exchangers for improved dehumidification in HVAC systems [6], while Lazzarin and Gasparella analyzed combined heating and cooling systems for enhanced energy efficiency [7]. In Thailand, Watchrodom et al. evaluated residential-scale thermosyphon heat pipes and reported significant improvements in energy savings and indoor comfort [8–10]. Srihajong et al. applied heat pipes to regulate moisture in aeroponic environments [11], and Meena et al. examined oscillating heat pipes in agricultural drying processes [12]. In parallel with these technological developments, research on building-envelope innovation has highlighted the growing importance of passive cooling strategies in reducing thermal loads

in tropical climates. Studies such as [13–16] have emphasized the effectiveness of ventilated roof structures, aerodynamic green-roof systems, and thermally optimized façade configurations in dissipating heat and reducing latent and sensible heat transfer across the building envelope. These findings demonstrate that passive systems, when strategically integrated with hybrid or active cooling approaches, can significantly reduce cooling demand and improve environmental performance in hot and humid regions.

Despite these advancements, limited research has examined the direct integration of thermosyphon heat pipes with evaporative cooling systems for enhanced dehumidification under naturally hot and humid conditions. There remains a critical knowledge gap in understanding the performance of such hybrid systems under real environmental fluctuations without mechanical or refrigerant-based assistance. Therefore, this study aims to address that gap by experimentally evaluating an evaporative cooling system augmented with thermosyphon heat pipes, focusing on its capacity to reduce humidity and improve overall thermal comfort in tropical climates.

## **2. RESEARCH SIGNIFICANCE**

This research advances the development of hybrid cooling systems by integrating thermosyphon heat pipes into an evaporative cooling configuration to reduce moisture content in incoming air prior to the cooling stage. Pre-conditioning the air in this manner enhances latent cooling performance and improves the overall effectiveness of evaporative cooling in hot and humid tropical climates, where conventional systems typically struggle to achieve substantial temperature reduction. The proposed system operates without requiring additional electrical power for dehumidification, allowing it to function as a passive and energy-efficient solution. This characteristic aligns with current efforts to minimize reliance on refrigerant-based air-conditioning technologies and to promote environmentally responsible approaches to indoor climate control. The experimental findings of this study are expected to contribute valuable empirical evidence that supports the design and optimization of next-generation hybrid cooling systems that reduce energy consumption and mitigate the environmental impacts associated with mechanical air conditioning.

## **3. EXPERIMENTAL SETUP**

The experiment was conducted using a custom-designed hybrid cooling system that integrates an evaporative cooling unit with thermosyphon heat pipes. The full assembly was installed on an open rooftop to accurately represent natural ambient conditions without artificial environmental control. This installation method ensures that the system

operates under real outdoor fluctuations in temperature, humidity, and solar radiation, allowing the performance evaluation to reflect practical field conditions, as shown in (Fig. 1).

At the center of the setup is a thermally insulated cubic test chamber with internal dimensions of  $100 \times 100 \times 100 \text{ cm}^3$ . The chamber consists of a steel structural frame covered with double-layered plywood, while the interior is lined with 5 cm of high-density thermal insulation to minimize conductive heat transfer. A 60-watt incandescent bulb was placed inside the chamber to provide a constant internal heat load representative of small residential or utility spaces. This artificial heat source helps maintain a controlled internal condition for comparing system performance across different outdoor environments. Upstream of the chamber, a centrifugal fan is used to draw ambient air through a pre-conditioning module made up of five vertically oriented thermosyphon heat pipes. Each copper pipe (9.5 mm in diameter and 40 cm in length) is filled with R-134a refrigerant and equipped with aluminum fins to enhance heat rejection at the condenser section. These heat pipes operate entirely through passive thermosyphon action, allowing moisture in the incoming air to condense on the cooled pipe surfaces. This process reduces the absolute humidity of the air before it reaches the evaporative cooling unit, effectively improving dehumidification capabilities. The evaporative cooling section consists of a cellulose cooling pad measuring  $33 \times 33 \times 10 \text{ cm}^3$ , with two 12-V axial fans positioned behind the pad to force air through the wetted material. This enables additional sensible and latent heat transfer, lowering the air temperature before it is supplied to the test chamber. Environmental parameters, including dry-bulb temperature and relative humidity, were monitored at four measurement points: ambient air, upstream of the heat pipe section, downstream of the heat pipe section, and inside the chamber. Calibrated K-type thermocouples ( $\pm 0.5^\circ\text{C}$  accuracy) and digital hygrometers were used to maintain high measurement reliability. Solar radiation during the experiment was continuously recorded using a pyranometer to document natural changes in irradiance.

Testing was carried out on two separate days representing different solar radiation levels: a moderate-radiation day averaging  $600 \text{ W/m}^2$  and a higher-radiation day averaging  $750 \text{ W/m}^2$ . Measurements were taken every 30 minutes between 12:00 and 15:30. Although natural variations in irradiance occurred, the selected intervals exhibited stable enough patterns to allow statistically meaningful comparisons. Grouping the results by average daily irradiance enabled a clear assessment of system performance under two distinct environmental conditions without relying on controlled laboratory conditions.



Fig.1 Experimental setup of the hybrid evaporative cooling system integrated with heat pipes

#### 4. ANALYZE DATA

The analytical framework for evaluating the evaporative cooling system integrated with thermosyphon heat pipes was developed based on the principles of steady-state mass and energy conservation. In this system, the airflow and thermal interactions were considered under quasi-adiabatic conditions, assuming minimal heat loss to the environment due to the insulated test chamber and short processing time. The predominant processes occurring within the system were heat and moisture exchanges between the ambient air, the evaporative medium, and the heat pipe assembly. As the ambient air enters the system, it first passes through the heat pipe array, where a portion of the water vapor is condensed due to the refrigerant's phase change within the pipes. This process reduces the moisture content of the incoming air through latent heat extraction, resulting in a slight increase in dry-bulb temperature. Following this stage, the pre-conditioned air flows through the evaporative cooling pad, where both sensible and latent heat exchanges occur, lowering the dry-bulb temperature while increasing the humidity ratio.

To analyze these thermal phenomena, the energy balance was applied to the moist air stream, which includes both the dry air component and the associated water vapor. The enthalpy change of the moist air was used as a performance indicator to quantify system behavior and energy transfer across each stage. The total enthalpy was calculated based on psychrometric properties, combining sensible heat and latent heat contributions. The conceptual diagram illustrating the mass and energy exchanges across the system, which includes both the heat pipe section and

the evaporative pad (Fig.2). This diagram provides a visual summary of the airflow pathway, component interactions, and measurement points used in the experiment. It serves as a reference for interpreting the performance results in the following section.

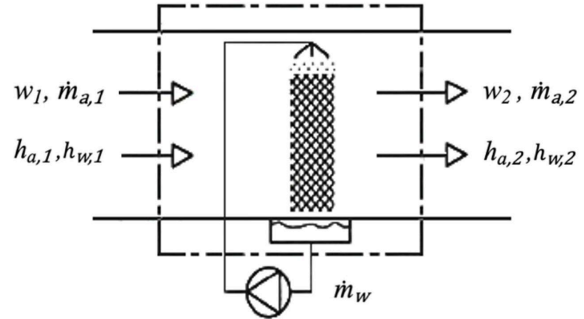


Fig. 2 Schematic diagram of mass and energy balance in evaporative cooling process

To determine the mass of evaporated water, the conservation of mass for water vapor is written as:

$$\dot{m}_w = \dot{m}_a(W_1 - W_2) \quad (1)$$

Where  $\dot{m}_w$  is the rate of water evaporation (kg/s),  $\dot{m}_a$  is the mass flow rate of dry air (typically 0.05 kg/s in this experiment), and  $W_1$  and  $W_2$  are the humidity ratios ( $kg_{water}/kg_{dry\ air}$ ) at the inlet and outlet of the cooling section, respectively.

The total enthalpy of moist air at any point is calculated as the sum of the enthalpies of dry air and water vapor:

$$h_{total} = C_{p,a}T + W(h_{fg} + C_{p,v}T) \quad (2)$$

Where  $C_{p,a} = 1.006$  kJ/kgC is the specific heat of dry air,  $C_{p,v} = 1.84$  kJ/kgC is the specific heat of water vapor,  $T$  is air temperature ( $^{\circ}C$ ),  $h_{fg} = 2450$  kJ/kg is the latent heat of vaporization, and  $W$  is the humidity ratio at the respective state.

For the moisture-laden air entering the cooling media, the rate of heat transfer from the air to the water (which facilitates evaporation) is derived from the energy balance as:

$$Q = \dot{m}_a(h_1 - h_2) \quad (3)$$

where  $h_1$  and  $h_2$  are the total enthalpies of the air stream before and after the evaporative process, respectively.

The performance of the cooling process was evaluated by calculating the evaporative cooling effectiveness, given by:

$$\varepsilon = \frac{T_{db,in} - T_{db,out}}{T_{db,in} - T_{wb,in}} \quad (4)$$

Here,  $T_{db,in}$  and  $T_{db,out}$  are the dry-bulb temperatures before and after the evaporative section, and  $T_{wb,in}$  is the inlet wet-bulb temperature. This ratio quantifies the cooling performance relative to the maximum potential defined by wet-bulb depression.

The dehumidification efficiency of the heat pipe system was also analyzed by comparing relative humidity measurements before and after the heat pipe section. This is expressed as:

$$\eta_{dehum} = \frac{RH_{in}-RH_{out}}{RH_{in}} \times 100\% \quad (5)$$

### 5. RESULTS AND DISCUSSION

This experimental evaluation was conducted to investigate the extent to which integrating thermosyphon heat pipes into an evaporative cooling system can improve both temperature regulation and indoor humidity control. This section presents the findings derived from measured dry-bulb temperatures, relative humidity levels, and performance indicators calculated using the analytical framework and equations described in the preceding section. These results establish the baseline performance of the evaporative cooling system prior to heat pipe integration and provide a reference for subsequent comparison.

Before the installation of heat pipes, the standalone evaporative cooling system demonstrated a moderate ability to reduce indoor air temperature; however, its capability to manage indoor humidity remained limited. As shown in (Table 1) and (Fig. 3), indoor temperatures fluctuated between 26.5°C and 31.0°C, while inlet air temperatures ranged from 26°C to 30°C during the experimental period. These values indicate that although the evaporative cooling system provided sensible cooling by lowering the dry-bulb temperature relative to the outdoor environment, the indoor space was still susceptible to progressive heat accumulation. This was attributed primarily to external solar radiation and internal thermal gains generated by the heat source inside the test chamber.

The limited humidity regulation observed in this baseline condition aligns with the inherent limitations of traditional evaporative cooling systems. Because evaporative cooling relies on continuous evaporation of water to provide cooling, it inherently increases the moisture content of the supply air. In hot and humid climates, where ambient moisture levels are already high, this added humidity can diminish thermal comfort, reduce cooling effectiveness, and increase the risk of microbial growth or mold development in enclosed or poorly ventilated areas. The absence of an integrated dehumidification mechanism in conventional evaporative systems therefore limits their suitability for regions where both temperature reduction and moisture management are essential.

Given these constraints, enhancing evaporative cooling systems with a passive dehumidification component such as thermosyphon heat pipes presents a promising and energy-efficient approach. By reducing the humidity of incoming air before it passes through the evaporative medium, heat pipes can mitigate excess moisture while supporting more stable indoor conditions. This improvement is particularly relevant in tropical climates, where maintaining acceptable temperature and humidity levels is critical to indoor environmental quality and occupant comfort.

Table 1. Hourly variation of outdoor, inlet and indoor temperatures before heat pipe installation

Time	Outside temperature	Temperature before entering the room	Room temperature
12:00	33	26	27
12:30	31	27	26.5
13:00	33	28	29
13:30	32	29	30.5
14:00	33	30	30
14:30	33.5	29.5	30.5
15:00	34	29.5	30
15:30	34.5	29	31

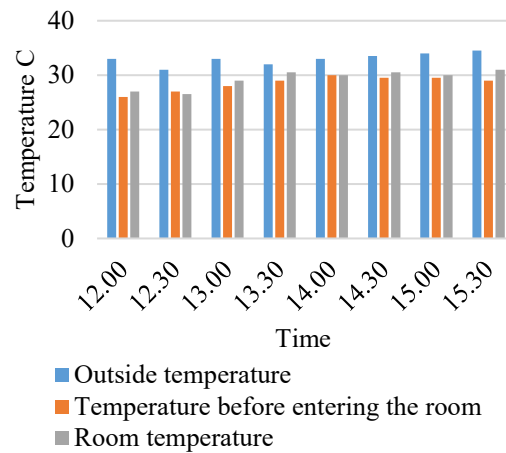


Fig.3 Temperature profiles before the installation of heat pipes

In parallel with the temperature results, (Table 2) and (Fig. 4) show that the relative humidity inside the room consistently exceeded outdoor levels throughout the experimental period, reaching values as high as 80% during peak times. This pronounced increase in indoor moisture content is directly associated with the continuous water vapor introduced by the evaporative pad. The saturation

effect reduces the system’s overall cooling capacity because high humidity suppresses the wet-bulb depression, thereby limiting the achievable evaporative effectiveness as defined in Eq. (4). Elevated humidity of this magnitude not only diminishes thermal comfort but can also lead to long-term issues such as condensation risk and reduced air quality within enclosed spaces.

Table 2. Hourly variation of outdoor and indoor relative humidity

Time	Outdoor humidity	Indoor humidity
12:00	57	77
12:30	53	80
13:00	55	75
13:30	54	67
14:00	55	68
14:30	58	66
15:00	57	68
15:30	59	64

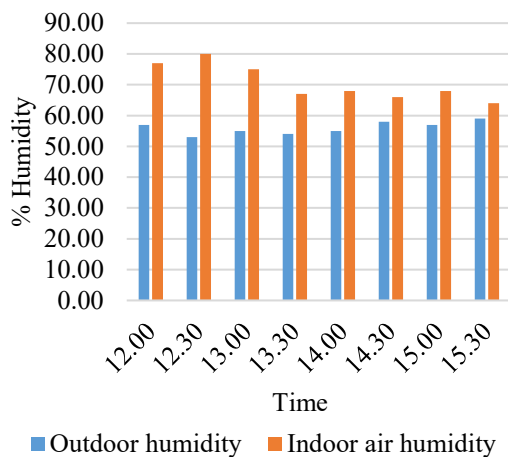


Fig.4 Relative humidity trends before the installation of heat pipes

Following the installation of the thermosyphon heat pipe section, a substantial improvement in both thermal and moisture behavior was observed. The passive dehumidification provided by the heat pipes effectively lowered the humidity ratio of the incoming air before entering the evaporative pad, enabling more efficient latent and sensible cooling within the test chamber. Under moderate solar intensity (600 W/m<sup>2</sup>), the temperature trends shown in (Fig. 5) indicate that the room temperature stabilized between 28°C and 30°C, exhibiting significantly lower fluctuation compared to the baseline condition. When exposed to higher solar radiation of 750 W/m<sup>2</sup>, (Fig. 6) demonstrates a similar thermal response, with peak indoor temperature

approaching 31°C. Despite the increased external heat load, the indoor temperature consistently remained below the outdoor range of 33–34.5°C, confirming the system’s enhanced thermal buffering capability.

Overall, the introduction of thermosyphon heat pipes improved both temperature stability and humidity regulation, providing a more balanced indoor environment under varying solar radiation conditions.

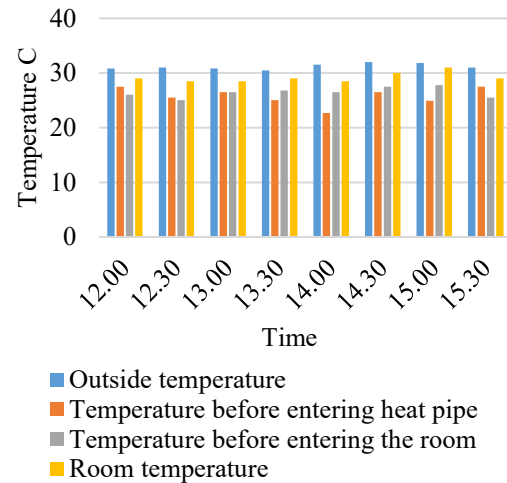


Fig.5 Temperature trends under 600 W/m<sup>2</sup> solar intensity

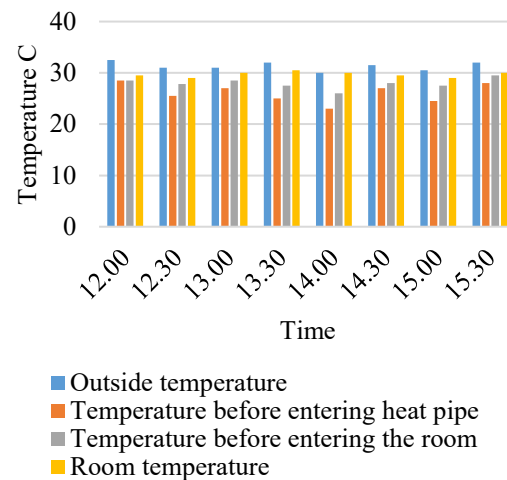


Fig.6 Temperature trends under 750 W/m<sup>2</sup> solar intensity

The experimental results reveal a consistent reduction in relative humidity across both test conditions, demonstrating the effectiveness of the thermosyphon heat pipe system in enhancing latent heat management. The air entering the heat pipe section exhibited noticeably higher relative humidity than the air exiting the system, confirming the successful extraction of moisture through the phase-

change mechanism, as described by Eq. (1). Under moderate solar radiation at approximately  $600 \text{ W/m}^2$ , relative humidity values declined from 74–77% at the inlet to 66–69% at the outlet; similarly, under higher radiation at  $750 \text{ W/m}^2$ , humidity levels decreased from 76–82% to 67–70%. These reductions, referenced in (Figs. 7-8), correspond to a dehumidification efficiency reaching up to 12.5%, based on Eq. (5).

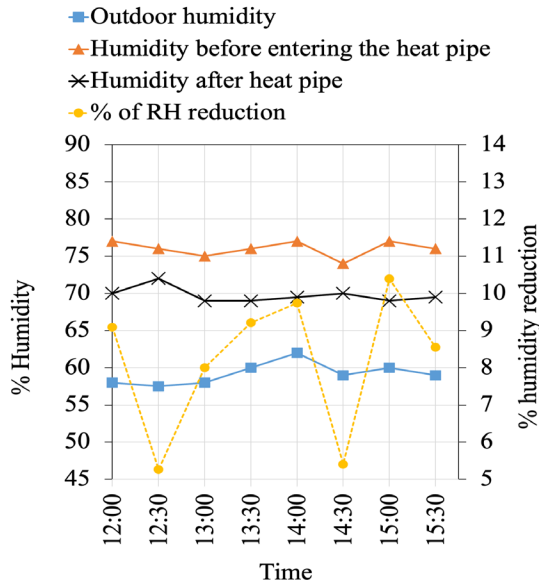


Fig.7 Trends of Relative Humidity and Dehumidification Efficiency Before and After Heat Pipe under  $600 \text{ W/m}^2$  Solar Radiation

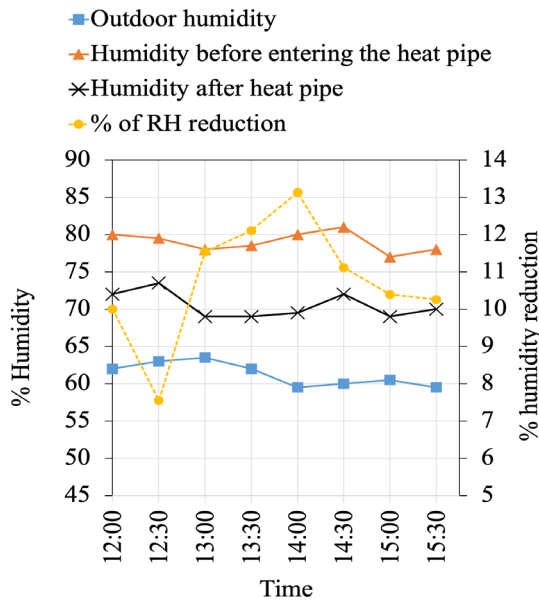


Fig.8 Trends of Relative Humidity and Dehumidification Efficiency Before and After Heat Pipe under  $750 \text{ W/m}^2$  Solar Radiation

This enhanced performance under elevated radiation levels is primarily attributed to the increased thermodynamic activity of the R-134a refrigerant, where higher ambient temperatures facilitate more intensive latent heat absorption and subsequent vapor condensation inside the heat pipes. As a result, the humidity ratio of the incoming air is significantly reduced before it reaches the evaporative cooling medium, thereby alleviating the latent cooling load. This pre-conditioning effect not only improves evaporative cooling effectiveness but also contributes to improved thermal comfort, as the system achieves a more substantial temperature drop with less residual indoor humidity. The integration of thermosyphon heat pipes thus proves to be a valuable passive enhancement for evaporative systems operating in humid tropical climates.

This pre-conditioning step alleviated the latent load on the evaporative pad, leading to an improved cooling effect with lower moisture saturation in the room. As a result, the evaporative cooling effectiveness, calculated using Eq. (4), increased in comparison to the baseline system. The air felt drier and more comfortable, particularly during afternoon hours with peak solar radiation.

## 6. CONCLUSION

This study experimentally evaluated a hybrid cooling system that integrates thermosyphon heat pipes with an evaporative cooling configuration to address the long-standing limitation of humidity buildup in evaporative systems operating under hot and humid tropical conditions. The results clearly demonstrate that incorporating a passive dehumidification stage prior to the evaporative medium provides measurable improvements in both temperature reduction and humidity control when compared to a conventional evaporative cooling setup. Before the installation of heat pipes, the standalone evaporative system exhibited moderate capability in lowering indoor dry-bulb temperatures but was unable to prevent moisture accumulation inside the test chamber. Indoor relative humidity frequently exceeded outdoor levels, reaching up to 80%, which diminished thermal comfort and reduced the effectiveness of evaporative cooling. These baseline findings reaffirm the well-known limitation of evaporative systems in climates where high ambient humidity suppresses wet-bulb depression and limits achievable cooling capacity.

Following the integration of thermosyphon heat pipes, significant enhancements in system performance were observed across all test conditions. The phase-change process within the heat pipes enabled effective extraction of moisture from incoming air, resulting in reductions of 6–12% in relative humidity depending on solar radiation intensity. Under moderate irradiance ( $600 \text{ W/m}^2$ ),

humidity decreased from 74–77% at the inlet to 66–69% at the outlet; under higher irradiance (750 W/m<sup>2</sup>), humidity declined from 76–82% to 67–70%. These reductions correspond to a dehumidification efficiency of up to 12.5%, confirming the capacity of heat pipes to function as a passive and energy-free dehumidification mechanism.

Temperature regulation also improved notably. The heat pipe section helped stabilize indoor temperatures between 28°C and 30°C under moderate irradiance and prevented temperatures from exceeding 31°C under high irradiance, despite outdoor temperatures reaching 34.5°C. This consistent thermal buffering effect indicates that the pre-conditioning of air not only reduces the latent load on the evaporative pad but also enhances sensible cooling performance. As a result, the evaporative cooling effectiveness improved relative to the baseline system, and the indoor air felt substantially drier and more comfortable, particularly during peak solar periods. Overall, the experimental findings provide compelling evidence that thermosyphon heat pipes serve as an effective passive enhancement for evaporative cooling systems in humid tropical climates. By lowering humidity before the evaporative stage and enabling more efficient heat and moisture exchange, the hybrid system achieves improved thermal comfort without relying on additional electrical energy or refrigerant-based mechanisms. These advantages align with global efforts to promote low-energy, environmentally responsible cooling technologies and suggest that hybrid evaporative–heat pipe systems hold strong potential for applications in residential, agricultural, and small-scale commercial buildings in tropical regions.

Future work may explore the long-term operational stability of the heat pipes, scaling strategies for larger building applications, and integration with other passive envelope innovations such as ventilated roofs or green-roof assemblies to further enhance system performance.

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