



## Thermal Performances of CLOHP in Attic Cooling with Flat Metal Sheet Roof

Nopparat Seehawong\*, Ninnart Rachapradit\*, and Piyanun Charoensawan\*,<sup>1</sup>

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**Abstract** – This research developed a prototype of a flat metal sheet roof utilizing a closed-loop oscillating heat pipe (CLOHP) to dissipate heat from the attic. The study will examine two roof designs: a bare roof and a roof with CLOHP that utilizes forced air-cooling using an exhaust fan. Additionally, the study will investigate the effects of solar intensity at 200, 400, and 600 W/m<sup>2</sup>, using a solar simulator equipped with halogen lamps to replicate solar energy, on the system's performance. The findings indicate a direct correlation between solar intensity and the temperatures of the roof surfaces and attic for all tested configurations. Notably, the CLOHP-equipped roof demonstrated superior performance, achieving an attic temperature of 38 °C under the maximum solar intensity of 600 W/m<sup>2</sup> and a heat transfer rate of 66 W. These results correspond to significant reductions of 22% in temperature and 57% in heat transfer compared to the standard bare roof. Moreover, the developed roof system is easy to construct, user-friendly, and requires negligible maintenance.

**Keywords** – attic, closed-loop oscillating heat pipe, flat metal sheet roof, thermal performances.

### 1. INTRODUCTION

Roofs serve as the primary pathways for solar heat entering buildings. Prolonged exposure to sunlight raises attic and indoor temperatures, creating thermal discomfort. Consequently, effective roof cooling is vital to alleviate indoor heat, reduce air-conditioning demand, and lower energy consumption. Numerous studies have explored this topic, with particular emphasis on enhancing solar reflectance to improve energy efficiency. In recent years, passive daytime radiative cooling using reflective coatings, films, and membranes has received increasing attention [1].

According to the literature [2], the effectiveness of a cool roof hinges on three primary characteristics: its ability to reflect a high degree of solar radiation, provide substantial thermal insulation, and efficiently dissipate absorbed heat. One representative concept is the Cool-Green Roof [3], which integrates reflective surfaces with vegetative layers. The vegetation improves reflectivity, strengthens insulation, and reduces roof surface temperature.

Both passive and active cooling strategies have been investigated to enhance thermal comfort [4]. For instance, systems combining reflective coatings, solar-powered fans, and automated rainwater cooling achieved attic temperature reductions of up to 6.5°C. Additional features, including compact cooling towers, photovoltaic panels, and power filters, further enhanced overall performance.

Other innovative approaches replaced conventional roofing with lightweight foam concrete, hollow slabs, reflective paints, and solar-powered insulation. Under strong solar radiation (829 W/m<sup>2</sup>), these designs lowered attic temperatures from 41.9°C to 33.9°C, corresponding to a 19.2% reduction in solar heat gain [5]. Investigations on roof tiles also revealed that material, shape, color, and surface finish strongly influence thermal performance, with glazed clay tiles showing superior results compared to concrete alternatives [6].

In the present work, flat metal sheet roofs are adopted due to their low weight, durability, affordability, and ease of installation. To improve cooling effectiveness, a closed-loop oscillating heat pipe (CLOHP) is introduced as a passive thermal management device. Prior studies have demonstrated the potential of heat pipes in reducing energy consumption in air-conditioning systems, particularly through wickless and U-shaped heat pipe exchangers [7]–[9].

A CLOHP's ability to transfer heat relies on a unique mechanism: the self-propelled, oscillating motion of a liquid-vapor mixture within its tubing. This movement is driven entirely by internal pressure changes that occur as the working fluid repeatedly evaporates and condenses. The overall effectiveness of this process is not fixed; it is highly dependent on a range of variables. Key factors to consider include the physical layout of the tubing (geometric design), the thermodynamic characteristics of the fluid, the precise amount of fluid inside (filling ratio), the device's angle relative to gravity, and the intensity of the heat source being applied [10]–[13]. Due to their fast thermal response and high efficiency, CLOHPs have been successfully employed in compact electronics cooling, where they maintained significantly lower device temperatures than uncooled conditions [14], [15].

Applications of CLOHPs have also extended to renewable energy and HVAC systems. In solar thermal

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\*Department of Mechanical Engineering, Faculty of Engineering, Naresuan University, 99 Moo 9 Phitsanulok-Nakhonsawan Road, Muang, Phitsanulok, 65000, Thailand.

<sup>1</sup> Corresponding author;  
Tel: + 66 815 965 900  
E-mail: [piyanunc@nu.ac.th](mailto:piyanunc@nu.ac.th)

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utilization, an extra-long OHP was integrated into a thermosyphon water heater [16]. Constructed from copper tubing with a 2.0 mm inner diameter and six meandering turns, and charged with distilled water, the system achieved stable operation at a 70% filling ratio. A flat-plate collector containing ten CLOHPs (20 turns each, 2.8 mm outer and 1.5 mm inner diameter) covering  $1.5 \text{ m} \times 1.0 \text{ m}$  attained a thermal efficiency of 0.67 under solar irradiation levels of 947–1086  $\text{W/m}^2$  [17].

In another application, a CLOHP system was developed to reduce the cooling load of air conditioning units by transferring heat between the incoming fresh air and the exhaust stream [18]. The unit operated effectively in both horizontal and bottom-heat orientations, achieving efficiencies in the range of 30–50%.

Its application in roof cooling has been reported; however, only a single relevant study has been found in the limited existing literature [19]. The potential for CLOHP-based roof cooling was demonstrated in a key experiment by Saw *et al.* (2021). Their research contrasted the performance of a typical bare metal roof with an identical one enhanced by a CLOHP system. To remove heat, their design uniquely featured a condenser section enclosed in a liquid-cooling apparatus, which connected to an evaporator mounted directly beneath the roof panel. Ethanol was selected as the working fluid, circulating within a 6.35 mm outer diameter copper tube to achieve the cooling effect. A prior study demonstrated a 13% reduction in attic temperature by utilizing a CLOHP-cooled roof. The system's configuration involved an evaporator attached beneath the roof, transferring heat to a condenser located within a box that circulated cooling water. Despite this result, the study did not assess the crucial influence of solar intensity on performance. Moreover, significant practical limitations were identified with the water-cooling approach: it is difficult to implement, necessitates additional water pumps, and leads to higher operational costs, including the need for a water discharge method. These initial investment and operational cost factors were not considered in the original study.

Based on the document provided, this study has four primary goals:

- To construct and test a prototype of a flat metal sheet roof that incorporates a closed-loop oscillating heat pipe (CLOHP) system installed on its underside.
- To employ a straightforward and practical air-cooling method at the CLOHP's condenser section.
- To conduct a comparative analysis of the thermal performance between two different roof setups: a standard bare roof and one equipped with a CLOHP using forced-air cooling from an exhaust fan.
- To evaluate how the system's thermal performance is affected by varying levels of solar intensity, specifically at 200, 400, and 600  $\text{W/m}^2$ .

## 2. FUNDAMENTAL CONCEPTS

### 2.1 Closed-Loop Oscillating Heat Pipe

The closed-loop oscillating heat pipe (CLOHP), shown in Figure 1, is composed of a long, small-diameter capillary tube bent into multiple meandering turns connecting the evaporator and condenser sections. The fundamental principle of a CLOHP relies on the oscillating two-phase flow of a working fluid, which exists as a series of liquid slugs and vapor bubbles. The cycle initiates at the evaporator, where applied heat causes the liquid to vaporize. This vaporization generates expanding bubbles, leading to a localized pressure increase that propels the fluid mixture toward the colder condenser section. As the vapor condenses back into liquid at the condenser, the resulting pressure differential sustains the pulsating, back-and-forth motion that enables highly efficient heat transfer.

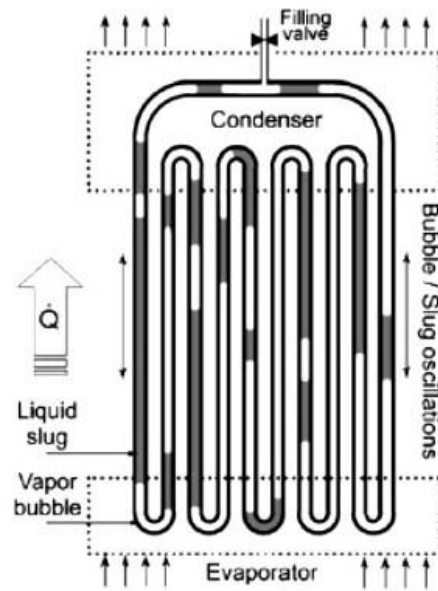


Fig. 1. Closed-loop oscillating heat pipe [10].

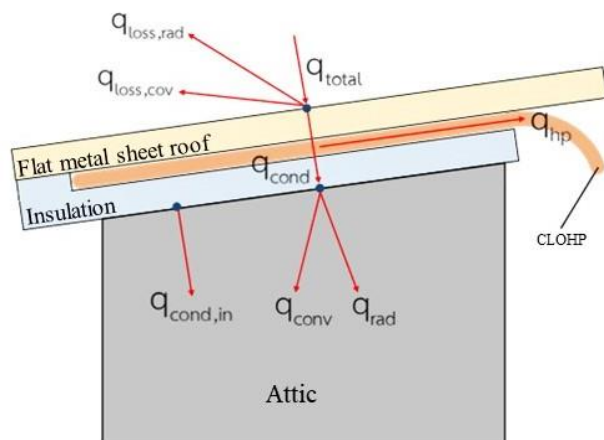


Fig. 2. Heat transfer system.

## 2.2 Heat Transfer of the System

When the roof absorbs energy from solar radiation, it converts the sunlight into heat, causing the outer surface temperature of the roof to rise. A fundamental difference in thermal pathways distinguishes the two roof designs. For the standard bare roof, incoming solar energy is either reradiated and convected away into the surrounding environment or conducted directly through the material into the attic below, raising its temperature. The CLOHP-integrated roof, however, adds a critical third pathway for heat management as depicted in Figure 2. This system functions as an active heat shunt, intercepting a substantial portion of the absorbed thermal energy and redirecting it away from the structure before it has the chance to infiltrate the attic space. When heat passes through the evaporator section of the heat pipe, which is attached beneath the roof and covered with thermal insulation, the heat is transferred to the working fluid inside the CLOHP. The working fluid then moves to the condenser section, located outside the simulated attic, where the heat is dissipated into the air passing over the condenser surface through forced convection using an exhaust fan. This process helps reduce heat transfer into the attic and lowers the temperature within the simulated attic.

Where  $q_{total}$  is the total heat transfer rate, converted from solar intensity generation and absorbed by the upper surface of the roof (W),  $q_{loss,conv}$  is the free convection heat loss from the roof (W),  $q_{loss,rad}$  is the heat loss by radiation from the roof (W),  $q_{cond,in}$  is the heat transfer rate into the simulated attic (W) which consists of convective heat transfer ( $q_{conv}$ ) and radiative heat transfer ( $q_{rad}$ ) and  $q_{hp}$  is the heat transfer rate of the CLOHP for roof cooling (W). Therefore,

$$q_{total} = q_{loss,conv} + q_{loss,rad} + q_{cond,in} + q_{hp} \quad (1)$$

$$\text{and } q_{cond,in} = \frac{T_{int} - T_{attic}}{R_t} \quad (2)$$

where  $T_{int}$  is the lower surface temperature of roof,  $T_{attic}$  is the attic temperature and  $R_t$  is total thermal resistance from the lower surface of roof to the attic which is shown in Figure 3. The  $R_t$  is calculated as follows:

$$R_t = \frac{R_{conv} \cdot R_{rad}}{R_{conv} + R_{rad}} \quad (3)$$

where  $R_{conv}$  is the heat convection resistance and  $R_{rad}$  is the heat radiation resistance. The  $q_{hp}$  is calculated as follows:

$$q_p = \dot{m} c_p (T_o - T_i) \quad (4)$$

where  $\dot{m}$  is the mass flow rate of air passing over the condenser surface of CLOHP,  $c_p$  is the air specific heat

and  $T_o$  and  $T_i$  are the air temperatures at outlet and exit of the condenser.

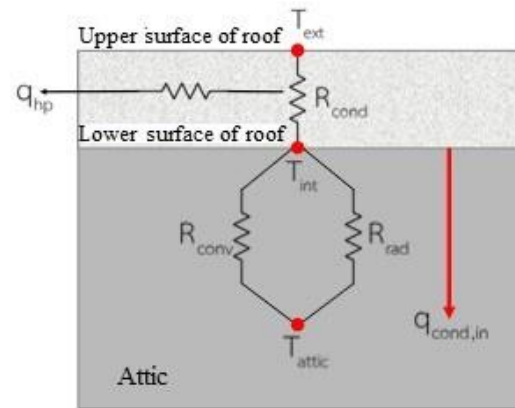


Fig. 3. Thermal resistance circuit.

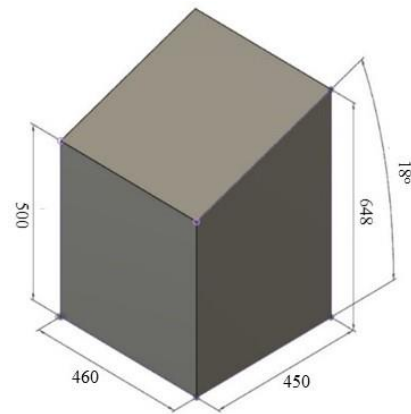
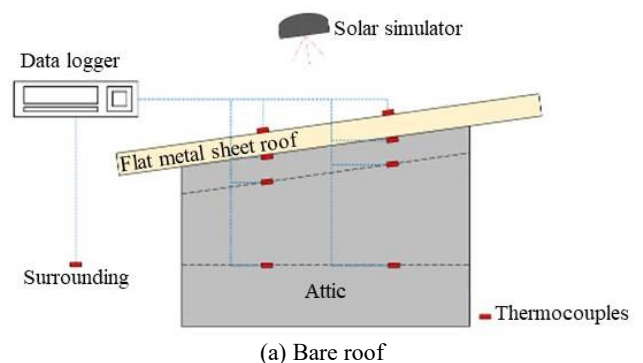


Fig. 4. Dimensions of simulated attic (mm).

## 3. EXPERIMENTAL SETUP AND PROCEDURE

A prototype of a simulated attic was constructed with dimensions shown in Figure 4, and the various roof designs are illustrated in Figure 5. The dimensions were adapted to align with the research by Saw *et al.* [19], but the roof angle was adjusted to 18°, which better suits the direction of sunlight in Thailand. The roof designs include a bare roof and a roof with the CLOHP that dissipates heat using forced air convection with a fan.



(a) Bare roof

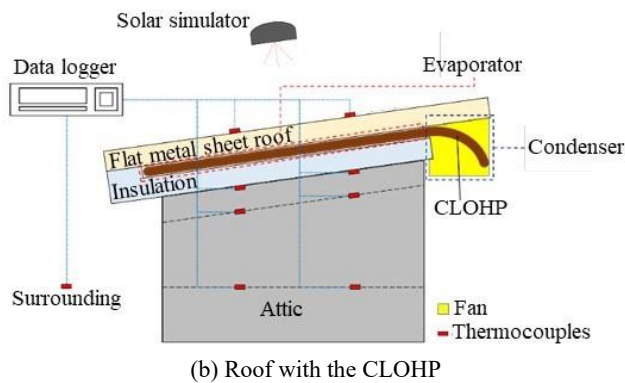


Fig. 5. Roof designs.



Fig. 6. Tested CLOHP.

The core of the experimental setup was a simulated attic built from 40 mm-thick Shera Pro Board. This structure was covered by a 540 mm x 600 mm standard brown metal sheet roof, 0.3 mm thick, to mimic typical construction. Key properties of the roof included a smooth surface, thermal conductivity of 211 W/m.K, and solar absorptivity of 0.9. A 10 mm-thick, white-silver PE thermal insulation was used, matching the roof's dimensions. This insulation had a thermal conductivity of 0.029 W/m.K, solar reflectivity of 0.86, and thermal resistance of 1.563 K/W. The Closed-Loop Oscillating Heat Pipe (CLOHP) was constructed from a 53.4-meter-long copper capillary tube. The tube had an internal diameter of 1.5 mm and an external diameter of 2.3 mm and was formed into 42 meandering turns. The device, shown in Figure 6, had an internal volume of 98 cm<sup>3</sup> and was filled to 50% capacity with distilled water [10], which is the optimal ratio for this working fluid. The tested CLOHP is shown in Figure 6. The solar simulator consists of two halogen lamps, each with a power of 1,500 W. The light intensity was adjusted using two dimmers. Halogen lamps emit a significant amount of infrared radiation (heat), which helps to replicate the thermal aspect of sunlight. This was advantageous for experimental research, as it allowed the solar intensity to be controlled and maintained at a nearly constant level throughout the experiment [16]. An exhaust fan with a size of 120 mm, an input voltage of 220-240 volts, a speed of 2,550 rpm, and an airflow rate of 2.3 m<sup>3</sup>/min was also included. During the tests, temperatures at various locations were measured

using K-type thermocouples (with an accuracy of  $\pm 0.5^{\circ}\text{C}$ ), and the solar intensity was measured with a pyranometer (with an accuracy of  $\pm 10\%$ ). The air velocity was measured with a hot-wire air velocity meter (with an accuracy of  $\pm 3\%$ ).

Each experimental run was initiated by activating the solar simulator and calibrating its output to the desired intensity (200 W/m<sup>2</sup>) using a pyranometer. Data logging of temperatures at all specified points commenced immediately and continued for a 30-minute period, which was predetermined as sufficient time for the system to achieve thermal equilibrium (steady state). To ensure reliability, the entire experimental procedure was duplicated for solar intensities of 400 W/m<sup>2</sup> and 600 W/m<sup>2</sup>. For each intensity level, a total of three independent trials were performed. The data collected were then analyzed. In the case of the roof with a CLOHP and forced cooling using a fan, the fan was switched on to draw air through the condenser section of the heat pipe at the beginning of the test.

## 4. RESULTS AND DISCUSSION

The variables under study included solar intensity and two roof configurations, which affected the temperature at various locations within the system. These factors directly influenced the cooling performance in the attic space and the thermal performance of CLOHP. Thermocouples were installed to measure the temperature at various locations, as shown in Figures 5(a) and 5 (b). The experiment revealed that from the start of the test to 30 minutes, the temperature changes at the upper surface of the roof, the lower surface of the roof, and the temperature inside the simulated attic of each roof type exhibited similar trends: the temperatures at different positions of the roof increased over time, eventually reaching a steady state around 30 minutes. Therefore, the experimental results from the steady state were taken into consideration.

### 4.1 Roof and Attic Temperatures

Figure 7 shows the relationship between the upper surface temperature of the roof and solar intensity for both the bare roof and the roof equipped with a CLOHP. A consistent thermal response was observed across all roof configurations: higher solar intensities, ranging from 200 to 600 W/m<sup>2</sup>, invariably led to elevated roof temperatures resulting from greater solar heat absorption. However, at the same level of solar intensity, the temperatures of the different roof types do not differ significantly. At solar intensities of 200 W/m<sup>2</sup>, 400 W/m<sup>2</sup>, and 600 W/m<sup>2</sup>, the upper surface temperatures of both roofs range from 67°C to 69°C, 83°C to 85°C, and 96°C to 98°C, respectively. During the experiment, the room temperature for each test varied between 35°C and 37°C.

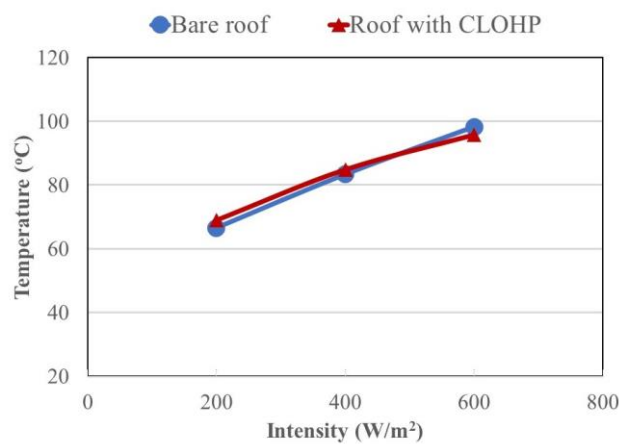
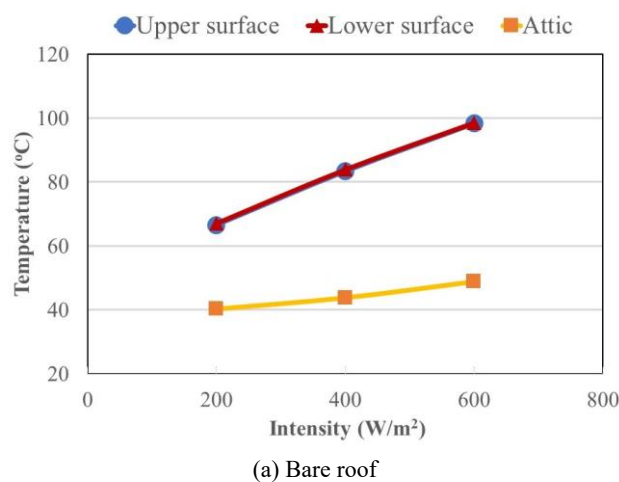
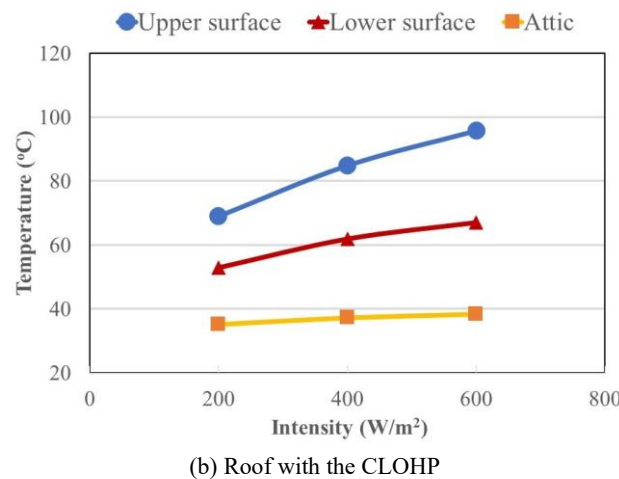


Fig. 7. Upper surface temperature of roof.



(a) Bare roof



(b) Roof with the CLOHP

Fig. 8. Roof and attic temperatures.

Figure 8 (a–b) shows the relationship between the upper and lower surface temperatures of the roof and the attic temperature with respect to solar intensity for both the bare roof and the roof with a CLOHP. For the baseline bare roof, a near-negligible temperature difference was recorded between the upper and lower surfaces, a result attributed to the material's thin 0.3 mm profile. This close thermal coupling meant the lower surface temperature escalated directly with solar

radiation levels. Specifically, measurements confirmed this trend, with the surface reaching 67°C, 83.5°C, and 98.5°C under solar intensities of 200, 400, and 600 W/m², respectively.

However, although the lower surface temperature of the roof with CLOHP also increases with solar intensity, it remains clearly lower than both its own upper surface temperature and the corresponding values for the bare roof. The temperatures are 53°C, 62°C, and 67°C for solar intensities of 200 W/m², 400 W/m², and 600 W/m², respectively. This indicates that the CLOHP effectively transfers a portion of the heat absorbed by the roof from solar irradiation to the ambient air. These results are further discussed in the next section.

As a result, the attic temperatures beneath the roof with CLOHP are lower than those beneath the bare roof at all solar intensities: 35°C, 37°C, and 38°C for 200 W/m², 400 W/m², and 600 W/m², respectively. Solar intensity has only a slight effect on the attic temperature for the roof with CLOHP, but a significant impact on that of the bare roof, which reaches 40°C, 44°C, and 49°C at the same intensities. This trend can be attributed to the operating principle of the CLOHP, where its heat transfer capability is directly proportional to the thermal energy it receives; in this experiment, a higher solar intensity provides a greater heat input, thus boosting its performance [13]. Therefore, as the solar intensity increases, the thermal performance of the CLOHP also improves.

Figure 9 shows the attic temperature reduction of the roof with CLOHP compared to that of the bare roof. It also includes data from Saw *et al.* (2021) [19]. The effectiveness of the CLOHP system in reducing attic temperature demonstrated a clear positive trend with solar intensity. Specifically, the temperature reduction climbed from 13% at 200 W/m² to 15% at 400 W/m², reaching a peak of 22% at 600 W/m². This improved cooling capability is directly linked to the enhanced operational performance of the CLOHP under higher heat loads, a characteristic that was noted earlier.

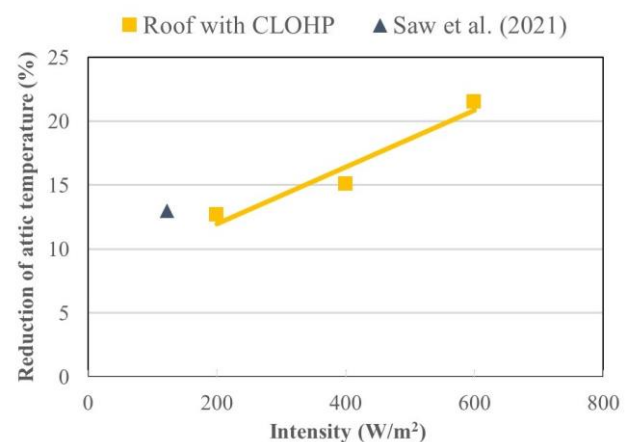


Fig. 9. Reduction of attic temperature.

For the data from Saw *et al.* (2021), the attic temperature reduction was 13% compared to a bare

metal roof at a solar intensity of  $123 \text{ W/m}^2$ . Figure 9 also presents a linear regression line derived from the relationship between solar intensity and attic temperature reduction in this study. It is found that at a solar intensity of  $123 \text{ W/m}^2$ , the attic temperature reduction tends to be slightly below 13%. This suggests that the CLOHP roof system developed by Saw *et al.* (2021) performed better than the system developed in this study. The superior performance is likely due to the higher density of cooling water used at the condenser, which provides a greater convection heat transfer coefficient compared to the cooling air used in the present study.

However, as mentioned in the Introduction, the system developed by Saw *et al.* (2021) also has certain disadvantages. In the present study, since the CLOHP condenser was cooled by ambient air, the number of meandering turns increased to 42 to enlarge the heat transfer surface area and improve heat dissipation from the roof to the air. A higher number of turns generally enhances the thermal performance of a CLOHP, especially when it operates near the horizontal axis [10]. The working fluid used in the tested CLOHP was distilled water, which has a high latent heat of vaporization. The total length of the copper capillary tube used (No. 16, I.D. 0.059") was 53.4 m, with a cost of approximately 1,000 Thai Baht (THB) per 60 m length. Therefore, the initial cost of the developed roof system is approximately 3,000 THB per square meter. Generally, the price of metal sheet roofing with insulation varies depending on several factors, including the thickness of the metal sheet, the type of insulation material, and the thickness of the insulation. In general, the cost ranges from approximately 190 to 2,200 THB per square meter.

Although this developed system is relatively expensive, it requires almost no maintenance due to the standalone operation of CLOHP. Moreover, for large-scale building applications, installing CLOHP beneath the entire roofing surface may be challenging due to structural limitations in supporting the weight of copper tubing across the whole roof. However, owing to the high thermal conductivity of flat metal sheet roofing, the CLOHPs may be distributed at selected intervals beneath the roof surface. This strategy reduces the required number and size of exhaust fans and the length of copper capillary tubes in the CLOHP system, which in turn decreases the initial investment cost of the cool-roof application. Furthermore, if small fans, like those used in the experimental setup, are employed, the noise generated is minimal and nearly imperceptible. It can be concluded that the developed roof system is simple to construct, user-friendly, and has negligible maintenance costs.

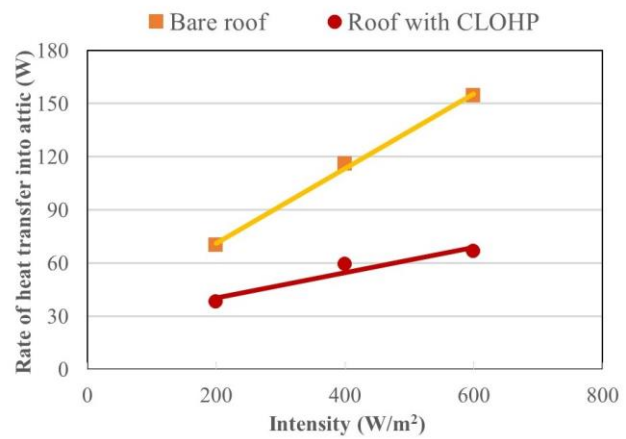


Fig. 10. Rate of heat transfer into the attic.

#### 4.2 Thermal Performances

Figure 10 presents the rate of heat transfer into the attic and the solar intensity for the two roof designs. The heat transfer rate into the attic was calculated using Equation (2). A clear distinction in performance emerges when analyzing the heat transfer rate into the attic under varying solar intensities. For the bare roof, this rate escalated sharply from 70 W to 155 W as solar intensity rose from 200 to  $600 \text{ W/m}^2$ . Conversely, the roof integrated with the CLOHP exhibited a much more stable and lower heat transfer rate, showing only a modest increase from 38 W to 66 W across the same intensity spectrum. The heat transfer rate into the attic for the roof with a CLOHP is consistently lower than that of the bare roof at all levels of solar intensity. This demonstrates that the tested CLOHP effectively removes heat from the metal sheet roof surface and transfers it to the ambient air before the heat reaches the attic. As solar intensity increases, the difference in heat transfer rate into the attic between the two roof types becomes more pronounced. The reduction ranges from 46% to 57% compared to the bare roof, for solar intensities between  $200 \text{ W/m}^2$  and  $600 \text{ W/m}^2$ , respectively. This improved performance is attributed to the increased heat input, enhancing the thermal performance of the CLOHP, as previously discussed.

Figure 11 shows the dependency of the CLOHP thermal performance and the heat flux into the attic on solar intensity. The heat flux of the CLOHP is defined as the ratio of the heat transfer rate of the CLOHP, calculated using Equation (4), to the roof area. Similarly, the heat flux into the attic is defined as the rate of heat transfer into the attic, calculated using Equation (2), per unit area of the roof.

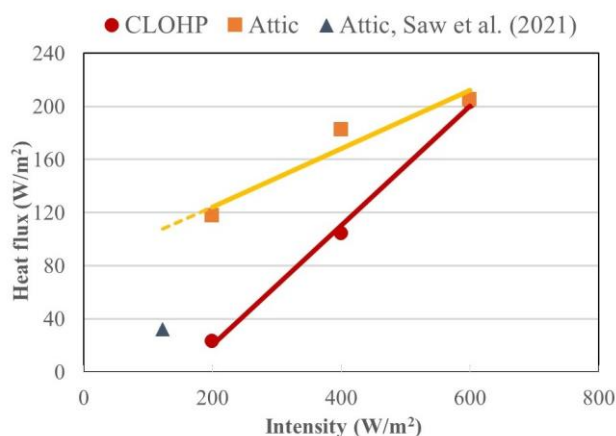


Fig. 11. Heat flux into the attic and of CLOHP.

The data reveal that while both the attic and CLOHP heat fluxes rise with solar intensity, their rates of increase differ markedly. The CLOHP heat flux, in particular, shows a much steeper climb, eventually nearing the attic's heat flux value with a measurement of approximately 204 W/m<sup>2</sup> under the highest solar intensity of 600 W/m<sup>2</sup>. For solar intensities of 200 W/m<sup>2</sup> and 400 W/m<sup>2</sup>, the heat fluxes into the attic are 117 W/m<sup>2</sup> and 182 W/m<sup>2</sup>, respectively, while the corresponding CLOHP heat fluxes are 23 W/m<sup>2</sup> and 104 W/m<sup>2</sup>.

Figure 11 also includes the data from Saw *et al.* (2021) [19] at a solar intensity of 123 W/m<sup>2</sup>, which shows a heat flux into the attic of 32 W/m<sup>2</sup>. In addition, linear trend lines for both the attic heat flux and the CLOHP heat flux from the present study were evaluated and plotted in the same figure. The dashed line indicates that the predicted attic heat flux in this study is approximately 107.5 W/m<sup>2</sup> at a solar intensity of 123 W/m<sup>2</sup>.

Moreover, the heat flux of the CLOHP is found to be essentially zero at this solar intensity, indicating that the tested CLOHP does not operate effectively under such low solar radiation. The lack of operation under low solar radiation is likely due to an insufficient heat supply at the evaporator. Without adequate thermal input, the system cannot generate the necessary pressure differential between the evaporator and condenser, which is the essential driving force required to initiate and sustain the fluid's oscillatory motion. Consequently, the CLOHP roof system developed in this study is more suitable for regions with high solar intensity, such as Thailand, particularly during the period between 10:00 a.m. and 3:00 p.m., when solar radiation is typically strongest.

## 5. CONCLUSION

Summary of experimental results:

- The developed prototype of a CLOHP-integrated flat metal sheet roof, featuring an air-cooled condenser, demonstrated successful and stable operation across the entire tested solar intensity range of 200-600 W/m<sup>2</sup>. Moreover, the developed roof system is easy to

construct, user-friendly, and requires negligible maintenance.

- A direct relationship was confirmed between rising solar intensity and elevated temperatures across all roof surfaces and within the attic for every configuration tested.

- The CLOHP's cooling effectiveness was found to be highly sensitive to solar intensity. Its performance is fundamentally governed by the thermal energy available at the evaporator, meaning higher intensity directly translates to more robust heat pipe operation and superior heat dissipation. As solar intensity increases, the heat flux of the CLOHP rises significantly and eventually nearly equals the heat flux into the attic, reaching about 204 W/m<sup>2</sup> at a high solar intensity of 600 W/m<sup>2</sup>.

- The CLOHP-integrated roof consistently outperformed the bare roof by maintaining a lower rate of heat transfer into the attic across all tested solar intensities.

- This peak performance was observed at 600 W/m<sup>2</sup>, where the system reduced the attic temperature to 38°C and heat transfer rate to 66 W, equating to impressive reductions of 22% and 57%, respectively, compared to the baseline bare roof.

## ACKNOWLEDGEMENT

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