

COMPARATIVE STUDY OF TWO COOLING FLUIDS USED IN CLOSED LOOP PULSATING HEAT PIPE ROOF SYSTEM FOR RESIDENTIAL BUILDINGS

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ABSTRACT

This paper presents the performances of Acetaldehyde and R22 refrigerant as working fluids for a closed loop pulsating heat pipe (CLPHP) cool roof system. We used two working fluids one after the other as the circulating fluids in a 404mm by 350mm roofing for an enclosure of 552mm by 350mm dimension. We used water as the cooling agent for the fluid condensation. The results showed that for the two working fluids, there is an average temperature difference of 3°C between the inside and the outside of the room. The discovery underscored the capability of the CLPHP cool roof system, showcasing its potential simplicity, cost-effective, and efficient alternative solution for improving thermal comfort in buildings located in tropical regions instead of the use of thermal mass walls.

Keywords: CLPHP, Heat Pipe, condensation, Tropical regions, Thermal Comfort

1.0 INTRODUCTION

Warm and humid climate conditions pose challenges for achieving optimal indoor thermal comfort [1]. Traditional buildings have been observed to perform better in terms of indoor thermal comfort compared to contemporary dwellings in warm, humid climatic regions [2]. Passive design strategies, such as appropriate building orientation, fenestration size and orientation, and use of materials, can contribute to achieving thermal comfort in warm, humid climates [1]. Human responses to warm-humid conditions are dependent on factors like temperature and thermal history, and the German addendum to the European standard EN 15251 may underestimate thermal sensation at elevated humidity levels [3]. Urban areas in warm and humid tropical regions experience high temperatures and humidity, leading to thermal discomfort and the urban heat island effect [4]. Climate-conscious building designs, including passive house performances, can improve indoor thermal comfort and reduce the need for mechanical ventilation in warm and humid climates. Tropical countries such as Nigeria have warm and humid climate conditions which give rise to high temperature throughout the year. Prolong exposure to such heat may impose a threat to human health [5]. As such the use of air condition and fan has become a way for the privilege to maintain comfort in their houses. Due to lack of electricity and rising cost of fuel it is becoming too difficult for many to afford. Hence, an innovative means in our building that provide comfort to the persistent thermal discomfort is needed in order to make our residential homes habitable [5].

Commonly used distinctive cooling methods for making our buildings habitable are grouped into active and passive cooling systems. Active cooling system uses electro-mechanical ventilators such as fan to generate airflow and expel heat from the structure [6]. Air conditional system utilize a refrigeration cycle to lower the temperature within the structure, water cooling, thermoelectric cooling are additional examples of active cooling method [6]. The disadvantage of active cooling system includes short life span, noise and energy

consumption. On the other hand, passive colling systems are designed to transfer heat from a component to an external portion without the need for external power.

Passive cooling is very important consideration for architects, engineers, and professionals in the building industry because it can play a great role in reducing energy cost for heat or cooling of indoor spaces as well as aesthetics [7]. In passive method the common practice among the engineers and construction workers in tropical countries is the use of materials with thermal mass and radiative cooling in building construction to reduce heat flow into buildings. The used of thermal mass in building our walls preserved the interiors of the building from the heat flow. However this isolation is practically difficult and cost a lot. Closed loop pulsating heat pipe (CLPHP) techniques is more practical. Examples of passive cooling are Vapor chamber, heat sink, heat pipe and closed loop pulsating heat pipe (CLPHP).

Close loop pulsating heat pipes (CLPHPs) are effective heat transfer devices that use the pulsating or oscillating actions of the working fluid to transfer heat. Pulsating heat pipes are highly efficient heat exchanger devices. It basically consists of an evacuated small diameter closed tube; bend in multiple turns, where a certain amount of working fluid is inserted. PHPs are composed of two main regions: evaporator, where heat is absorbed, and condenser, where heat is removed. The closed loop pulsating heat pipe (CLPHP) have better thermal performance than the open loop pulsating heat pipe (OLPHP) as they provide possibility of fluids circulation [8]. It was first invented by [9] in his US patent 4921041, The CLPHP operates with different working fluids at different fill ratios, such as water, methanol, and ethanol. The thermal performance of the CLPHP is evaluated based on parameters like temperature variation, thermal resistance, heat transfer coefficient, and thermal conductivity. Experimental studies and numerical simulations have been conducted to analyze the behavior and flow patterns of the working fluid in the CLPHP.

[10] studied Closed Loop Pulsating Heat Pipe (CLPHP) performance, analyzing factors like gravity, turns, and thermophysical properties. They explored variations in internal diameter, turns, working fluids, and inclination angle. [5] Saw et al. (2021) compared bare metal roofs to cool roofs with CLPHP, revealing a 12.94% thermal improvement and recommending cost considerations. [11] investigated CLPHPs made with copper capillary tubes, exploring diverse configurations with different working fluids in horizontal and vertical arrangements. [12] examined a copper tube multi-turn Pulsating Heat Pipe using ammonia, finding decreased thermal resistance with increased heat input. [8] analyzed the vertical performance of PHP with hydrophilic/superhydrophobic channels, comparing it to a fully hydrophilic PHP. [13] conducted experiments on a single-turn CLPHP in both horizontal and vertical orientations, showing superior performance in the horizontal orientation.

In this work, we used closed loop pulsating heat pipe system in maintaining the temperature for cooling the inside of the room. We used acetdehyde and R22 refrigerant as working fluids with copper pipe. These fluids have low boiling point to facilitate absorbing away the heat of the inside room.

2.0 THEORITICAL BACKGROUND

The heat flow in the roof system can be described using the following energy equation:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \frac{dE}{dt}. \quad (1)$$

For steady-state condition, Eq. (1) can be simplified to:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

where E is the energy in the room

The total heat from the radiation heat source (Q_{total}) is absorbed by the metal roof surface. Some of the heat absorbed are dissipated due to natural convection ($Q_{conv out}$) and radiation ($Q_{rad out}$), while the remaining heat ($Q_{cond in}$) is conducted to the attic. The energy balance equations for heat transfer at the metal roof surface and attic can be expressed as follows:

At metal roof surface:

$$Q_{total} = Q_{cond in} + Q_{conv out} + Q_{rad out} \quad (3)$$

Under full insulation condition and no heat gain and heat loss in the attic, the overall heat transfer to attic (Q_{attic}) can be calculated using Eq. (4):

$$Q_{attic} = Q_{cond in} = \frac{(T_{ext-roof} - T_{attic})}{R_t} \quad (4)$$

where R_t is resistance to convection heat transfer

3.0 DESIGNS AND PRINCIPLES GOVERNING THE OPERATION OF ROOF SYSTEMS.

The cool roof design comprises a metal roof sheet atop a CLPHP system, featuring copper tube construction. An insulating layer is placed between the metal roof and the CLPHP system. The roof is inclined at a 30° angle from the horizontal axis. Detailed information on the dimensions of system components and the physical properties of the roof system can be found in Table 1 and Table 2, respectively.

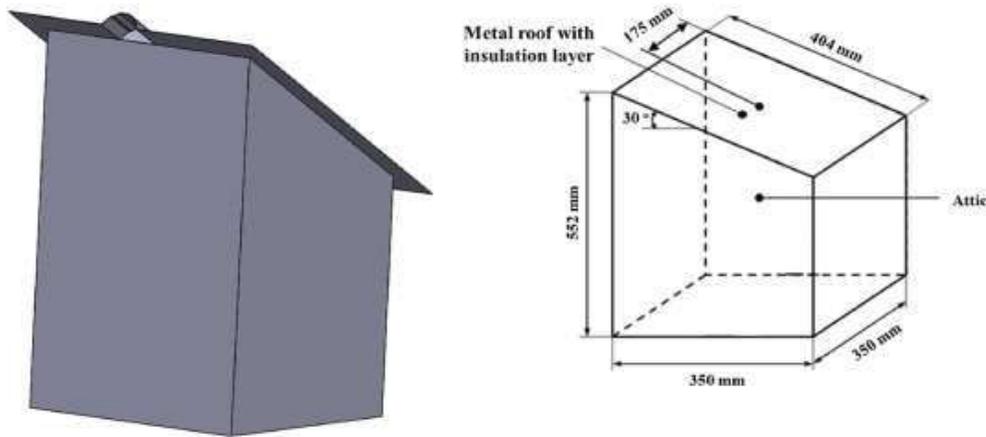


Figure 1: Metal Roof System [5]

3.1 Creation of the Clphp Cool Roof System Design

Figure 2 depicts the design of the CLPHP cool roof system. A circular copper tube, with an outer diameter of 6.35 mm, thickness of 1.5 mm, and a total length of 2460 mm, is bent into a loop with multiple U shapes. The pipe's both ends are extended adequately to create a closed-loop circuit using a T-connector. This T-connector facilitates fluid filling into the heat pipe, achieved through a syringe injector. Once the desired filling ratio is achieved, the control valve is closed.

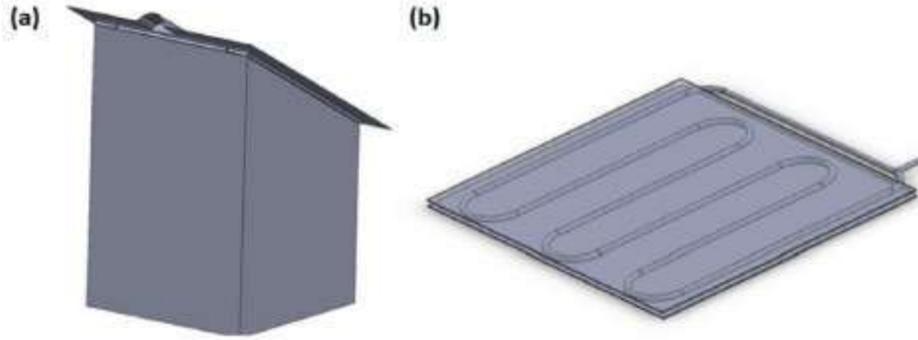


Fig. 2. (a). CLPHP cool roof system. (b) Side view of the CLPHP system.

A metal roof is placed atop the CLPHP system to preserve the building's aesthetics and shield the cool roof system. In this investigation, two working fluids, fluid 1 (acetaldehyde) and fluid 2 (R22 refrigerant), were employed with a filling ratio of approximately 80%, as indicated by the study conducted by [5]. This ratio was chosen to achieve the lowest evaporation and condenser temperatures. The CLPHP system is divided into two sections: the evaporator section, positioned beneath the metal roof, and the condenser section, situated atop the metal roof. The condenser section features an external loop circulating cooling water to dissipate accumulated heat. The operational mechanism of the CLPHP system is depicted in Figure 3.

As previously mentioned, the CLPHP system comprises an evaporator section and a condenser section. Utilizing fluid 1 (acetaldehyde) and fluid 2 (R22 refrigerant) as the working fluids, their properties are outlined in Table 3. In the evaporator section, latent heat transfer occurs, where a portion of fluid 1 (acetaldehyde) absorbs heat from the roof, transforming into vapor bubbles, while the remaining liquid slug absorbs sensible heat. As more vapor of fluid 1 (acetaldehyde) is generated, the vapor pressure in the evaporator section rises, ultimately pushing the acetaldehyde liquid slug into the condenser section due to the pressure difference. In the condenser section, acetaldehyde vapors are cooled by the outer-loop cooling water, condensing into liquid before returning to the evaporator section. This continuous process results in the oscillatory motion of fluid within the copper tube, and the same process applies to fluid 2 (R22 refrigerant).

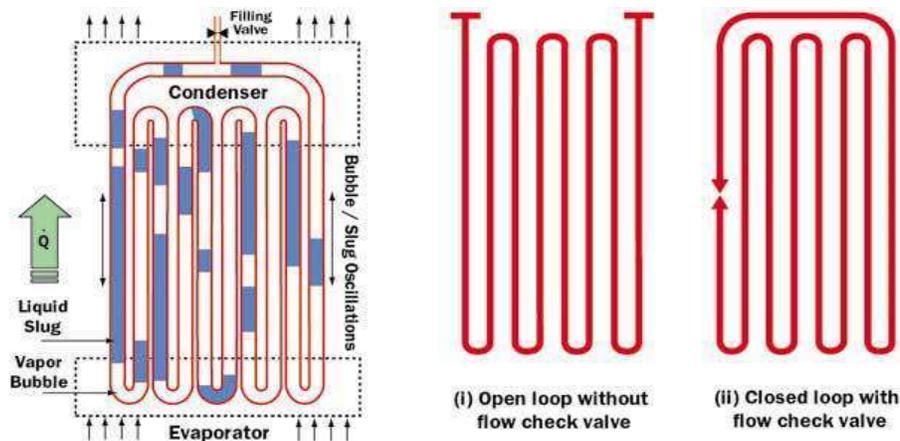


Figure 3: Operating Principle of CLPHP system [14]

Table 1: The Physical Characteristics of the Roof System

Component [a]	Density, kgm^{-3}	Specific heat capacity, $\text{Jkg}^{-1}\text{K}^{-1}$	Thermal conductivity, $\text{Wm}^{-1}\text{K}^{-1}$
Insulator	32	3450	0.0503
Galvanized zinc roof	7800	470	52
Attic	1190	1466	0.19
Copper tube (pipe)	8900	385	401

[a] [5]

Table 2: Dimension of the Copper Tube and Aluminum Plate for CLHP System

Component [b]	Diameter, D (mm)	Length, L (mm)	Width, W (mm)	Thickness, t (mm)	Surface Area, A (mm)
Copper tube	6.35	2460	-	1.5	79.74×10^3

[b] [5]

Table 3: Working Fluids Properties

Properties	Fluid 1 (Acetaldehyde) liquid	Fluid 2 (R22 Refrigerant) gas
Density, kg/m^3	788	1194
Vapour density, kg/m^3	-	3.03
Surface tension, N/m	65×10^{-3}	
Liquid specific heat capacity, kJ/kg. K	1240	
Vapour specific heat capacity, kJ, kg.K	-	1.0487
Boiling point $^{\circ}\text{C}$	20.2°C	-40.8
Latent heat of vaporization, kJ/kg	569	233
Liquid viscosity, mPa.s	0.295	
Thermal conductivity, W/mk	11	11.4

3.2 Experimental Setup

Plate 1 displays the schematic diagram of the experimental arrangement designed to assess the performance of the roof systems. Two thermocouples were used in this experiment. The first thermocouple terminal was placed inside the room and the second one outside the room shown in plate 1.

The experiment was conducted for 8 hours. The temperature values from the thermocouple were collected at an interval of 1hour from 8:30am to 4:30pm for the ten (10) days, five (5) days for each working fluid.

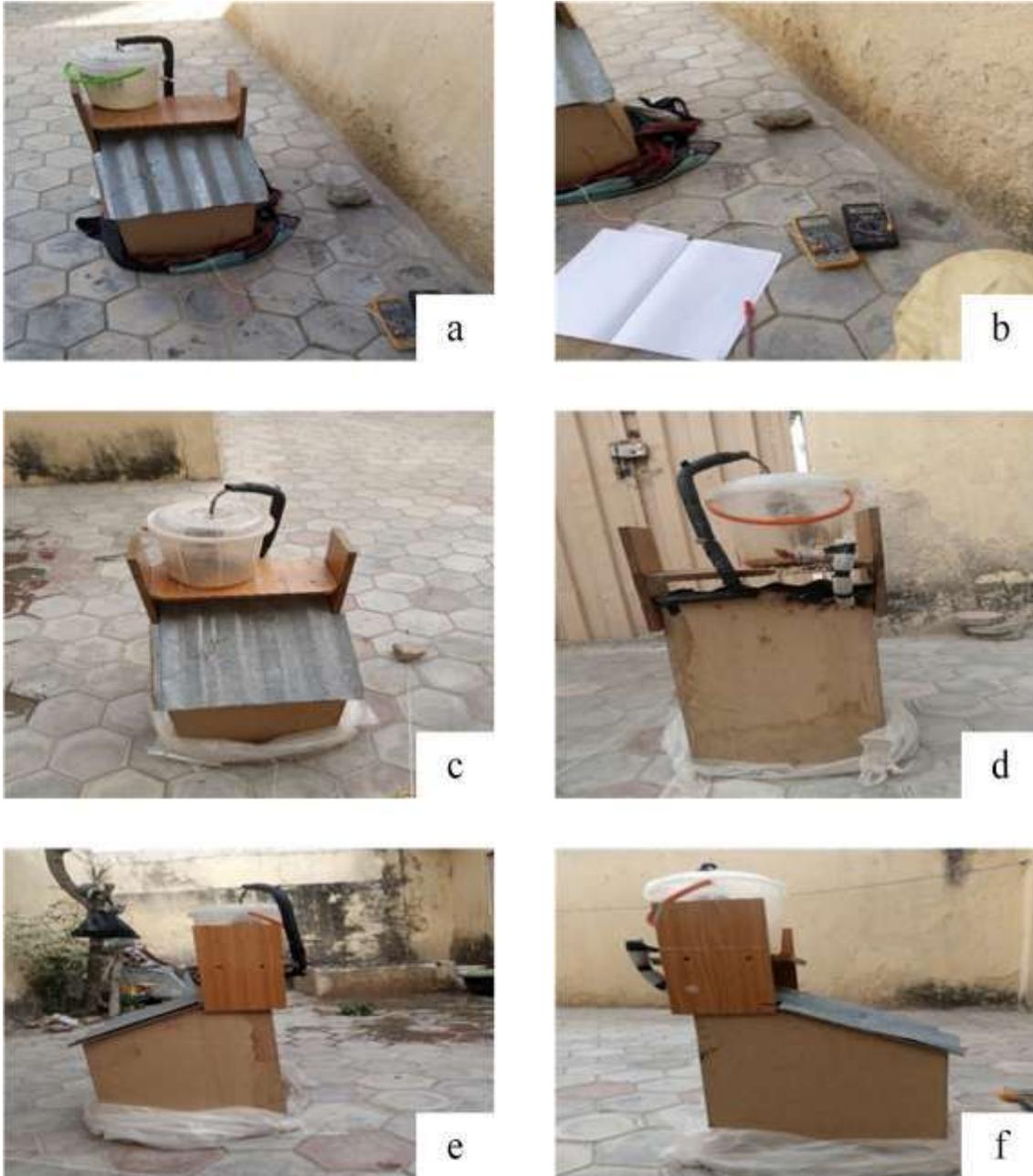


Plate 1: Different views of the experimental setup

4.0 RESULTS AND DISCUSSION

The results of the ten (10) days measurements of the temperature profiles of both inside and outside of the constructed CLPHP Cool system; five (5) days using fluid 1 (acetaldehyde) and (5) days using R22 refrigerant as fluid 2 are presented here.

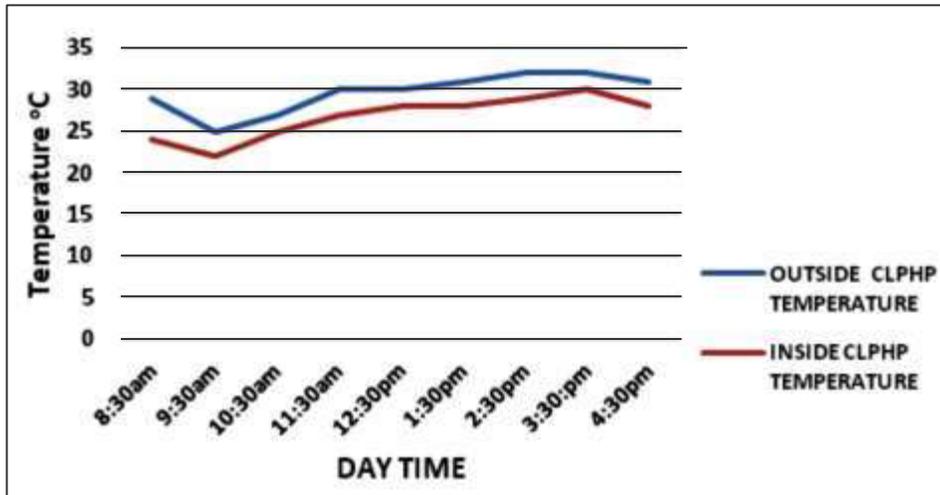


Figure 5: Temperature Profile for CLHP Using Acetaldehyde on Day 1

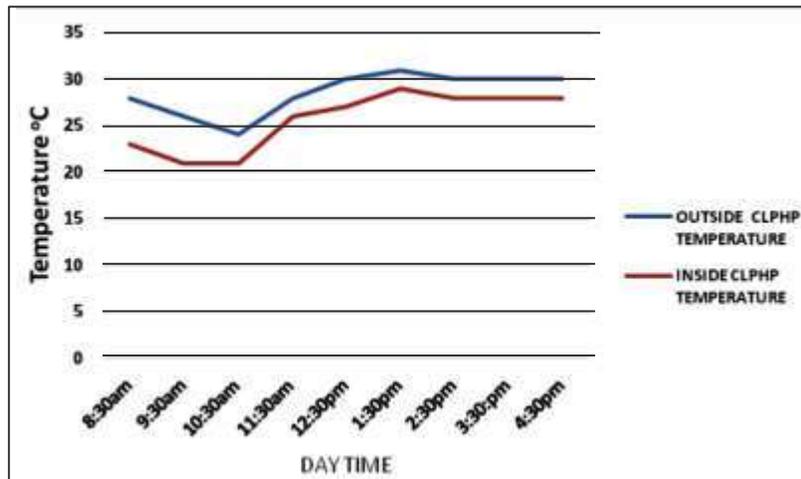


Figure 6: Temperature Profile for CLHP Using Acetaldehyde on Day 2

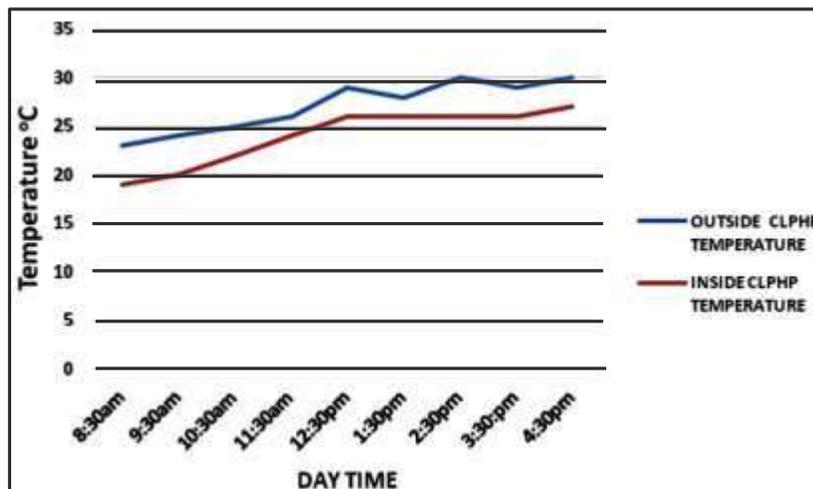


Figure 7: Temperature Profile for CLHP Using Acetaldehyde on Day 3

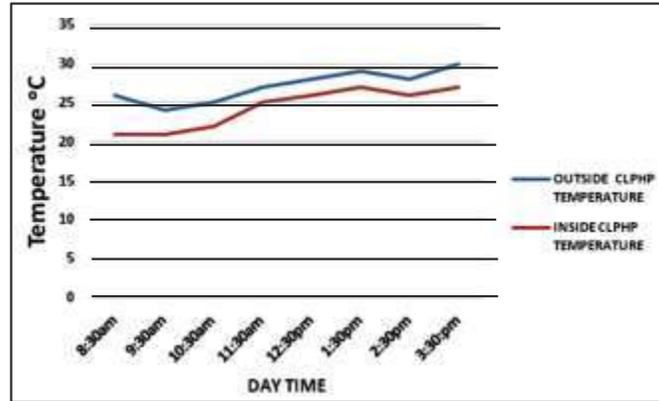


Figure 8: Temperature Profile for CLHP Using Acetaldehyde on Day 4

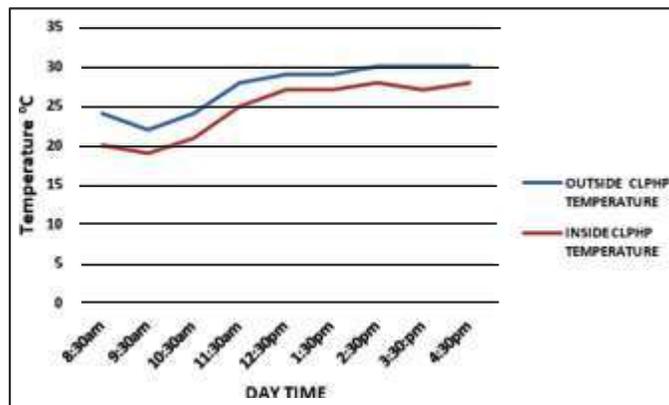


Figure 9: Temperature Profile for CLHP Using Acetaldehyde on Day 5

It can be seen from Figures 5 through 9, that the temperature of the inside of the constructed CLHP roof system using Acetaldehyde as working fluids have lower than those outside the roof system for all the five (5) days experiments. Curves of Figure 5 to 9, the temperature would go down in the first one hour before going up. This can be described to the fact that the working fluid 1 is in liquid form. As such at the commencement of the measurement (8:30am) the entire fluid 1 is in liquid form and would absorbed more energy from the room for some of it to be evaporated. It can also be seen from the curves that the peak temperatures for days occur at around 2:00pm.

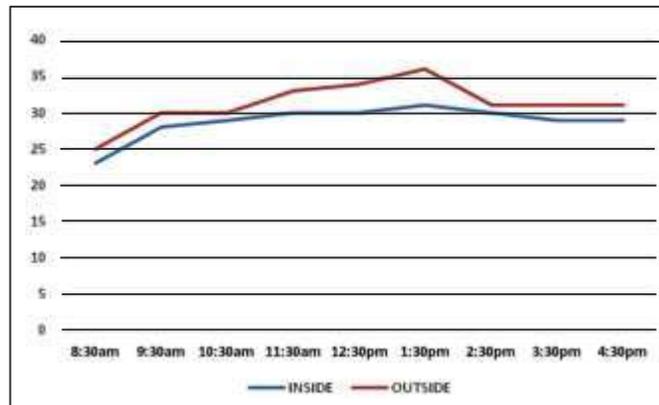


Figure 10: Temperature Profile for CLHP Using R22 refrigerant on Day 6

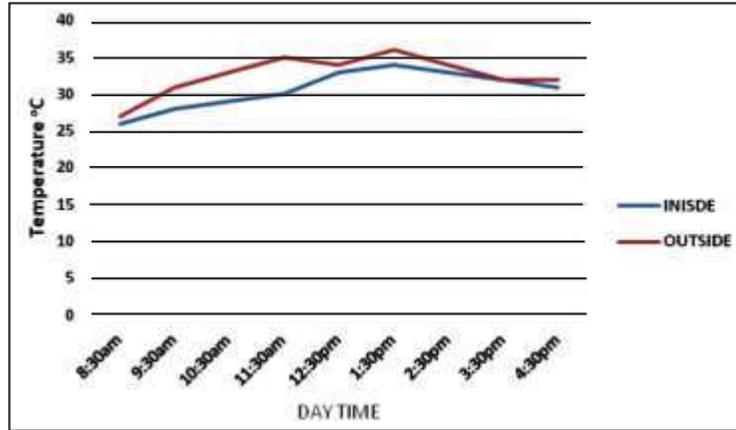


Figure 11: Temperature Profile for CLHP Using R22 refrigerant on Day 7

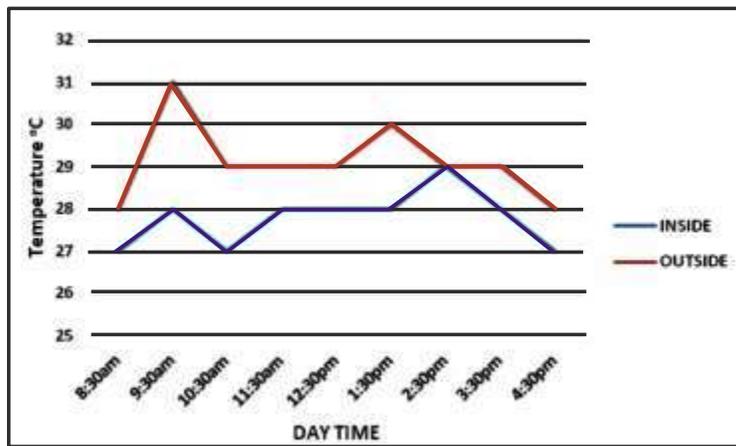


Figure 12: Temperature Profile for CLHP Using R22 refrigerant on Day 8

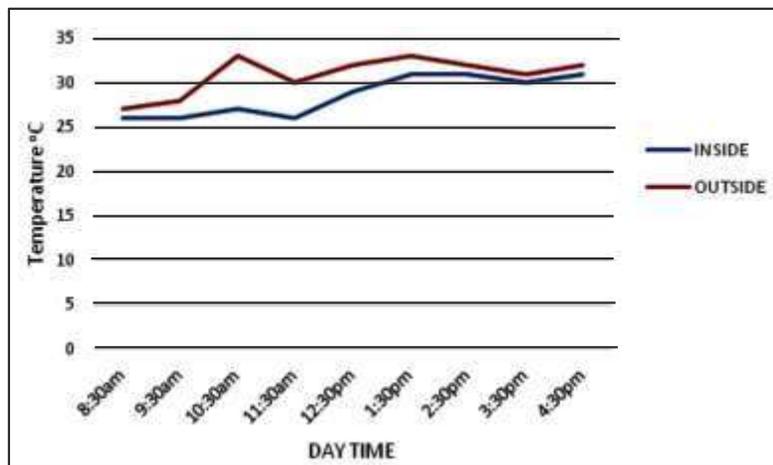


Figure 13: Temperature Profile for CLHP using R22 refrigerant on Day 9

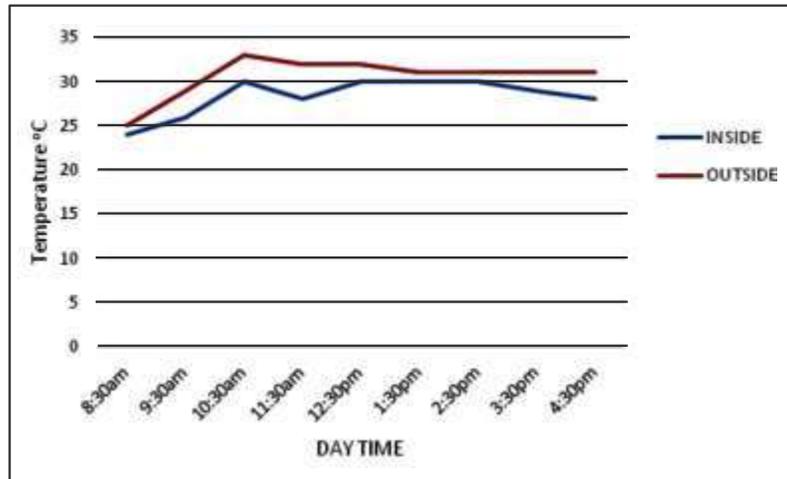


Figure 14: Temperature Profile for CLHP using R22 refrigerant on Day 10

It can be seen from Figures 10 through 14, that the temperature of the inside of the constructed CLHP roof system using R22 refrigerant as working fluids have lower than those outside the roof system for all the five (5) days experiments. The curves of Figure 10 to 14 at the beginning are all starting at the room temperature and move up as time goes on, fluid 2 is in gaseous form.

Hence, the present experimental results clearly demonstrate that the implementation of the CLPHP roof system has the potential to enhance thermal comfort in buildings with metal roofing.

5.0 CONCLUSION

We found that the use of CLPHP can sustain an average temperature difference between the inside and the outside of a room of about 3°C. This result is very close to that reported by [5] when they used methanol as their working fluid. It is also very significant compared to the corresponding reduction of about 7.2°C units that can be obtained when thermal mass walls were used in constructing the four walls of the room at hundred percent efficient. This is practically impossible as such the thermal mass walls would only have an average temperature gradient of around 4.2°C at about 65% efficiency. The thermal mass walls are at most four in number including the ceiling while our room is only outside; the ceiling, as such, in terms of cost, our CLPHP is by far less expensive compared to the cost of four walls of the thermal mass. This idea would be very useful and cheap for warehousing grains and other foodstuffs that tolerate few temperature rises. It can also be employed to improve the thermal comfort of our residential buildings.

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