Open Journal of Applied Sciences, 2024, 14, 2374-2392
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Experimental Assessment of the Thermal Performance of Two Corrugated Metal Roofs

Kouamé Jean-Louis Kouakou, Ekoun Paul Magloire Koffi*, Bi Tra Désiré Zinla, Prosper Gbaha

Laboratoire des Procédés Industriels, de Synthèse, de l'Environnement et des Energies Nouvelles, Institut National Polytechnique Felix Houphouët-Boigny, Yamoussoukro, Côte d'Ivoire
Email: *paumagloirel@yahoo.fr

How to cite this paper: Kouakou, K.J.-L., Koffi, E.P.M., Zinla, B.T.D. and Gbaha, P. (2024) Experimental Assessment of the Thermal Performance of Two Corrugated Metal Roofs. *Open Journal of Applied Sciences*, **14**, 2374-2392.
https://doi.org/10.4236/ojapps.2024.149157

Received: August 1, 2024
Accepted: September 7, 2024
Published: September 10, 2024

Abstract

This experimental study is a contribution to the search for solutions to reduce indoor heat gain through sheet metal roofing in hot weather. It has evaluated the thermal impact of two different sheet metal roofs inside of two identical test buildings in sunny weather and cloudy weather conditions. Test building 1 has a single sheet corrugated roof and the building 2 is covered with roof made from top to bottom with corrugated sheet metal, a 12 mm thick serpentine copper tube in which water is circulated, a sheet of aluminium foil acting as a heat reflector, a 4 cm thick polystyrene panel and a 1.5 cm thick plywood. A maximum reduction of 15.1˚C in the temperature of the inner face of the test Building 2 roof was obtained comparatively to the temperature of the inner face of the test Building 1 roof consisting of a single sheet of metal at the warmest hours. In addition, the simple corrugated sheet metal roof of the test building generates high and varied temperatures inside the building. Whereas the proposed heat recovery roof favours low and relatively uniform temperatures inside the building. The proposed sheet metal roof construction technique is very effective in reducing the heat gain through the roof considerably; thus improving the thermal comfort inside sheet metal roofed dwellings. Hot water has been produced by recovering heat from the metal sheet of the roof of test building 2. The temperature of the hot water produced reached of 39˚C. This study could be also an alternative for the reduction of energy consumption due to the use of mechanical means for cooling of sheet metal roofed houses and the reduction of the use of fossil fuels for domestic hot water production.

Keywords

Metal, Roof, Corrugated, Time Lag, Decrement Factor

1. Introduction

Human beings have been improving their habitats for centuries in order to protect themselves from rain, heat, cold, wind, snow and all kinds of dangers that can hinder their tranquillity and their lives [1]. One of the primary functions of the habitat is to create an indoor microclimate in which humans can rest or work without being subjected to heat and moisture pressure [2]. It is said that man is in atmosphere of comfort. This comfort zone depends on the type of climate and the region. The comfort zone for tropical climates is between 20˚C and 27˚C with a relative humidity between 20% and 70% and characterised by calm air, with air speeds below 0.1 m/s [3].

The thermal environment inside a building is the result of the thermal contributions of the roof and the interior walls. Indeed, the building receiving solar radiation reflects one part, the roof and the walls absorb the other part. This heat stored by the roof and walls is then transmitted differently inside the building by conduction, convection and radiation depending on the thermal characteristics of the different materials. The roof is the building element that directly receives the largest proportion of solar radiation compared to the other elements of the building envelope [1] [4]-[6]. Omar *et al.* [7] through a balance of the solar direct incident flux received by different parts of a building showed that the roof receives about 35% of all annual solar radiation. Furthermore, Joshi [8] showed that about 60% of the bulding's solar gains are made through the roof. A roofing material is said to be ideal for an efficient housing when it has a low thermal conductivity, low emissivity, high reflectivity, good strength, light, durable, waterproof, without tendency to condense the humidity indoors and economical [9].

As in many African countries, formerly roofs in Côte d'Ivoire were built with traditional materials (thatch, grass leaves, earthen slabs). These materials are excellent and cheap to reduce thermal stress [10] due to their low thermal conductivity. According to Hashemi *et al.* [11] the use of thatch or straw instead of metal sheets as roofing materials reduces the risk of indoor discomfort 15 times. However, thatch is less durable and has a high risk of fire; this has led people to adopt modern materials (sheet metal, concrete slab, tiles, etc.) [12]. Metal sheeting (corrugated sheeting, pan sheeting) is one of the most widely used roofing materials in recent decades in both rural and urban areas. In our tropics, this material is popular because of its quick installation, lightweight and design flexibility with the advantage of ensuring good sealing, safety, durability and economy with low cost installation. However, metal sheeting causes extremely unbearable or unpleasant indoor conditions. Indeed, it overheats very quickly during periods of high solar irradiation and becomes very cold by radiation to the night sky and during cold periods due to its rapid heat loss [13]. Therefore, the use of passive solutions in the construction of the roof with metal sheeting is essential for thermally efficient houses.

Several solutions are proposed in the literature to improve the thermal performance of metal sheeting in order to reduce heat gains during the day and/or night-time heat loss at night through the roof. Harimi *et al.* [14] have shown that for a sheet metal roof with a ventilated attic without insulation the maximum indoor air temperature is about 4.58˚C lower than the maximum outdoor air temperature. Through an experimental study, Geron [15] evaluated the performance of a naturally ventilated double-layer roof consisting of an upper aluminium-zinc cladding with an emissivity of 0.2 to 0.25 and a lower sheet metal cladding with an emissivity of 0.9. He obtained a reduction in indoor air temperature of about 3˚C during the day compared to the indoor air temperature of an identical building with a single sheet metal roof with an emissivity of 0.9. On the other hand, when cooling at night, the two temperature curves become identical again. Li *et al.* [16] by parametric analysis showed that increasing the aspect ratio and the angle of inclination of the ventilation cavity with respect to the horizontal favours better heat transfer convection through the cavity. In 2017, Omar *et al.* [7] showed that natural ventilation through the cavity of a 5 m roof inclined at an angle of 5˚ to the horizontal, with a sheet metal top layer leads to a reduction in energy consumption from 116 W/m^2 to 60 W/m^2 (*i.e.* almost 50% savings). In addition, the addition of 5 cm of insulation with a thermal conductivity of 0.035 W/mK on the inner part of the second layer forming the ventilated cavity results in better performance with 85% energy savings. According to Hashemi [17], roof insulation minimises the risk of overheating inside the house and thus improve the thermal comfort of occupants of low-income housing in Uganda. Kaboré *et al.* [1] showed that insulating the roof with single sheet metal without ventilation cavity with 5 cm thick plywood leads to less variation in indoor temperature. A time lag of 2 h between the times of reaching the maximum temperatures of the inner face of the plywood compared to the single sheet roof was obtained. However, with reflective white paint solution and the radiant barrier solution, the maximum temperatures of the inner faces of the roofs are reached at the same times as the single sheet case. Robelison *et al.* [18] evaluated the insulation solution under galvanised sheet metal commonly used in the central highland villages of Madagascar. They achieved a 16˚C reduction in air temperature in the ceiling cavity by employing under-roof insulation with 11.25 cm thick thatch of thermal conductivity equal to 0.045 W/mK. Yew *et al.* [19] studied the performance of applying reflective paint of thermal conductivity in the range of 0.107 to 0.129 W/mK on unventilated sheet metal. Maximum temperatures of the top and bottom surfaces of the sheet were obtained of 60.0˚C and 57.0˚C respectively were obtained; with a maximum difference of 3˚C. Ponni *et al.* [20] proposed a sandwich design technique for the galvanised metal top roof. They showed that the temperature of the inner side of the roof with a simple galvanised sheet metal covering during the warmest hours averages 44.3˚C while that of the insulated roof averages 33.8˚C, with a difference of 10.5˚C. However, the humidity inside the house with the insulated roof remains the highest compared to the house with the single sheet galvanised roof throughout the experiments. Wang *et al.* [21] showed that compared to the use of simple sheet steel roofing for prefabricated houses, the proposed insulation solutions reduce the air conditioning load consumed annually for indoor comfort. The use of reflective coating with a thermal reflectivity of 0.8 on the steel sheet leads to a 29.6% annual reduction in air conditioning consumption. However, insulation with vinyl plastic wrapped wood pieces with a thermal conductivity of 0.071 W/mK allows 33.9% of annual air conditioning loads reduction and the roofing combining insulation with plaster and wrapped wood pieces promotes a reduction of 40.5% of annual air conditioning loads.

This experimental study is a contribution to the search for solutions to the problem of thermal discomfort induced by the high heat transmission of metal sheet inside homes. The performance of a roof built with corrugated sheet metal capable of recovering a significant part of the heat under the sheet is evaluated in this study compared to a roof constructed with a simple sheet of metal. In fact, heat is recovered through the circulation of cold water in the serpentine tubes housed in the corrugations of the sheet. The study compares the temperatures of the inside faces of the two roofs. On the other hand, it evaluates the impact of the inside faces of the walls of the test buildings on the degradation of the thermal conditions inside the test buildings.

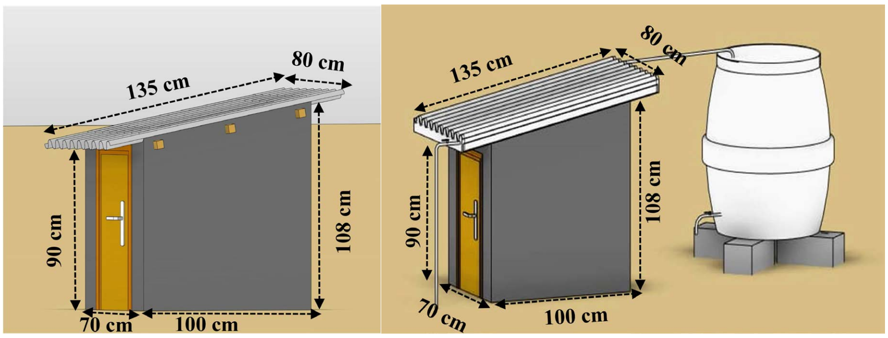
2. Materials and Methods

2.1. Description of the Test Buildings

The experimental set-up (**Figure 1**) was built in the workshops of the Department of Mechanics and Energy of the Institut National Polytechnique Félix Houphouët Boigny in Yamoussoukro, the capital city of Côte d'Ivoire, situated in Sub-Saharan Africa between 5˚ and 11˚ north. In order to improve the thermal performance of the sheet metal roof, two test buildings are constructed side by side with different roof configurations (**Figure 2**) without attic. Roof 1 is single corrugated roof and Roof 2 is a corrugated heat recovery roof.

Test building 1 has a simple corrugated metal roof (Roof 1) of dimensions (135 cm × 80 cm) installed on two rafters (6 cm × 5 cm). While test Building 2 is covered with a Corrugated heat recovery roof consisting of from top to bottom with a roof (**Figure 3**) consisting of a corrugated metal sheet (135 cm × 80 cm), 12 mm thick of serpentine copper tube in which water is circulated, a sheet of aluminium foil acting as a heat reflector, with long wave emissivity of 0.03 and short wave absorptivity of 0.10, 4 cm thick of polystyrene panel (120 cm × 75 cm), 1.5 cm thick of plywood (130 cm × 78 cm) acting as the interior ceiling and two rafters (6 cm × 5 cm). The walls of the test buildings are constructed with 15 cm thick hollow cement bricks and covered with 1.5 cm thick cement plaster. The dimensions of the walls of the test buildings are as follows: length (100 cm), width (72 cm), upper height (105 cm), lower height (80 cm). In addition, windows (30 cm × 20 cm) were made on the walls opposite the doors. Both roofs are inclined at 10˚ to the horizontal. Hot water is produced by recovering some of the heat from under the sheet metal through the circulation of low-flow water in the serpentine copper tubes housed in the corrugations of the corrugated sheet metal. This water is continuously discharged into a barrel insulated with 3 cm thick polystyrene. Table 1 gives the different thermal characteristics of the different materials in the test buildings.

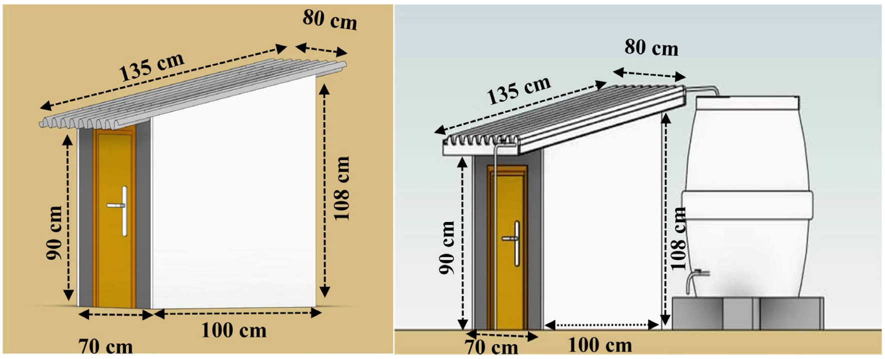
Figure 1. Buildings tests.



(a) Building test 1

(b) Building test 2

Figure 2. Configuration 1 of Buildings tests.



(a) Building test 1

(b) Building test 2

Figure 3. Configuration 2 of Buildings tests.

Two configurations are considered for the experiment. For configuration 1, test buildings 1 and 2 are without wall insulation with door closed and window closed. For configuration 2, the east and west walls of the test buildings are insulated with 3 cm thick polystyrene with door closed and window closed.

Table 1. Thermal characteristics of the materials used in the study [22] [23].

	Materials	Conductivity (W/m·˚C)	Thickness (m)	Specific heat (J/kg·˚C)	Density (kg/m^3)
Wall	Clay brick	0.9	0.15	3200	1000
	Interior coating	0.833	0.015	1000	1000
	Exterior coating	0.833	0.015	1000	1000
Door	Wood	0.0254	0.15	1630	608
Roof	Corrugated steel	50	0.002	450	7800
	Copper	385	0.001	385	8940
	Aluminium foil	-	0.001	-	-
	Polystyrene	0.035	0.04	-	-
	Wood	0.09	0.127	1170	592
Window	Wood	0.0254	0.15	1630	608

Exposed to solar radiation, the different external walls of the test buildings convert part of the received radiant energy into heat. This heat is transmitted to the internal walls of the test buildings by conduction in different ways depending on the thermal characteristics of the different materials making up the walls. Subsequently, the internal walls of the test buildings transfer the heat to the indoor air by convection and radiation. Compared to a roof covered with simple sheet metal, the combination of polystyrene, aluminium foil and tubes in which water circulates without a loop at a reduced flow rate under the corrugated sheet allows the heat recovered from the sheet metal to be transferred to the interior of the building. In this way, the solution of constructing the second roof in sheet metal reduces the heat inside the building in hot weather.

2.2. Instrumentation

The experimental study consisted of measuring the total incident solar radiation received by the roofs of the test buildings and the temperatures of the different external and internal walls of the test buildings. In addition, data on the interior and exterior humidity of the test buildings and the inlet and outlet temperatures of the serpentine cooper tube. Moreover, inside and outlet water temperatures of the barrel were measured. The total incident solar radiation is measured using a KIPP and ZONEN pyranometer with a relative measurement error of ±2%. It is connected to a digital integrator, of the same brand, allowing the reading of the solar energy received instantaneously and of the daily irradiation. The pyranometer is placed horizontally to obtain the full solar radiation. Temperature measurements were carried out with temperature sensors (NTC sensors) with a precision of ±0.1˚C and a measuring range of [−50˚C, +110˚C]. All the temperature sensors underwent prior calibration in a metrology laboratory using a standard Testo 925 thermometer with a relative error on the measurements (k = 2) of ±0.16˚C. The absolute error on the temperature measurements is ±0.2˚C. The relative humidities were measured with thermo-hygrometer sensors type DHT22 with a temperature accuracy of ±0.5˚C with a measurement range of [−40˚C; +125˚C] and a relative humidity measurement accuracy of ±2% with a measurement range of [0%; 100%]. The flow rate of water in the serpentine tube is calculated every hour.

For the instant, automatic and continuous reading of the data every 2 minutes, a data acquisition card is made. The different probes and humidity sensors of each test building were mounted on an Arduino electronic board. The data read by the Arduino board is retrieved, sent and stored in a database by Wi-Fi on a computer installed 30 metres from the test buildings. By recovering the heat from the sheet metal, hot water was produced continuously from 7:30 a.m. to 6:30 p.m. The tubes in the roof were continuously supplied with low flow tap water.

2.3. Roofs Performances Assessment

Assessment of the thermal performance of the two types of corrugated roofs will consist on the one hand of the comparison of the temperatures of the external and internal faces of the roofs versus time (**Figure 4**). The maximum and minimum temperatures reached by the inner and outer sides of the roofs are compared, as well as the hours at which these maximum and minimum values are reached. In addition, the decrement factor f and the time lag Φ of roof and walls are calculated. In fact, during the propagation of a heat wave through a building wall, the time difference between the time at which the outer wall reaches its maximum temperature and the time at which the inner wall reaches its maximum temperature is called time lag [24]-[26]. And the decreasing ratio of the amplitudes of the outer and inner roof or walls is called the decrement factor. These two parameters are calculated according to the formulas below. Indeed, a lower decrement factor with a larger time lag indicates that the roof has a good thermal performance.

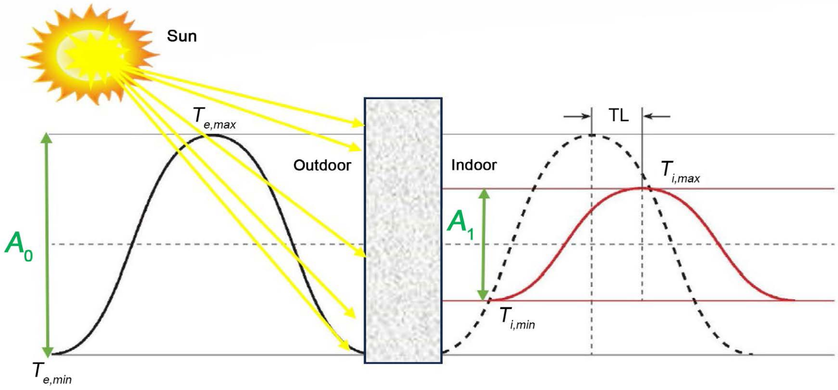


Figure 4. Heat propagation through an opaque wall and representation of time lag and decrement factor.

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \tag{1}$$

$$\Phi = t_{T_{i,\max}} - t_{T_{e,\max}} \tag{2}$$

where $T_{i,\max}$ is the maximum temperature of the inner roof or wall side of test building and $T_{i,\min}$ is the minimum temperature of the inner roof or wall side of test building and t refers to the time. $T_{e,\max}$ is the maximum temperature of the exterior roof or wall side of test building and $T_{e,\min}$ is the minimum temperature of the exterior roof or wall side of test building and t refers to the time.

3. Results and Discussion

All experiments were conducted in triplicate and the average of the temperatures was used to assess the thermal performances. The two tests for each configuration were performed in the same climatic conditions.

3.1. Evolution of the Temperatures of the External and Internal Sides of the Roofs as a Function of Time

The measurements of this experimental study were carried out under sunny weather conditions (configuration 1) and under cloudy weather conditions (configuration 2) in Yamoussoukro at latitude 6.58˚N. During the sunny day, instantaneous solar incident flux reached a maximum of 943 W/m^2 at 11:30 a.m. with a daily irradiance of 5705 Wh/m^2 and during the cloudy day, instantaneous solar incident flux reached a maximum of 1024 W/m^2 at 12:00 a.m. with a daily irradiance of 4730 Wh/m^2.

The maximum and minimum temperatures recorded for the different roofs and different walls sides of the buildings in configurations 1 and 2 are presented in **Table 2** and **Table 3**, respectively. We notice that the temperature curves of the inner side of the proposed roof (roof 2) as a function of time for both configurations are smooth compared to those of the roof constructed with a single sheet of metal (roof 1) which records very variable temperatures as a function of time due to its high thermal conductivity. This means that the proposed roof is less sensitive to variations in external weather conditions compared to the roof constructed with single sheet metal.

Table 2. Maximum and minimum temperatures of roofs, indoor air and ambient outdoor air for configuration 1.

Building test 1				
Sunny weather	$T_{\max}$ (˚C)	Hour (h:mm)	$T_{\min}$ (˚C)	Hour (h:mm)
Roof 1 outside temperature	53.46	13h00	23.6	06h30
Roof 1 inside temperature	50.90	13h00	24.70	06h30
Configuration 1 case internal air temperature	41.10	16h00	27.80	06h30
East wall outside temperature	42.11	11h00	24.66	6h30
East wall inside temperature	40.42	16h30	25.66	07h00
West wall outside temperature	47.27	16h00	24.54	6h30
West wall inside side temperature	42.79	17h30	25.65	07h30
North wall outside temperature	40.23	16h00	24.64	6h30

Continued

North wall inside temperature	39.98	17h30	25.84	07h30
South wall outside temperature	41.61	14H00	24.7	6h30
South wall inside temperature	39.47	16H00	25.3	6h30
Floor temperature	34.4	17H00	26.7	6h30
Ambient temperature	43.60	14h00	24.90	06h30
Building test 2				
Sunny weather	$T_{\max}$ (˚C)	Hour (h:mm)	$T_{\min}$ (˚C)	Hour (h:mm)
Roof 2 outside temperature	49.61	13h00	22.67	06h30
Roof 2 inside temperature	39.90	16h30	26.00	06h30
Configuration 1 case internal air temperature	39.60	17h00	25.90	06h30
East wall outside side temperature	42.91	11h00	24.92	6h30
East wall inside temperature	39.7	16h30	25.56	07h00
West wall outside side temperature	47.16	16h00	24.55	6h30
West wall inside temperature	42.74	17h30	25.6	07h30
North wall outside side temperature	40.18	16h00	24.82	6h30
North wall inside temperature	39.61	17h30	25.72	07h30
South wall outside side temperature	41.87	14H00	24.13	6h30
South wall inside temperature	39.58	16h30	25.45	6h30
Floor temperature	34.00	17h30	27.4	6h30

Table 3. Maximum and minimum temperatures of roofs, indoor air and ambient outdoor air for configuration 2.

Building test 1				
	$T_{\max}$ (˚C)	Hour (h:mm)	$T_{\min}$ (˚C)	Hour (h:mm)
Roof 1 external side temperature	53.54	13h30	25.85	07h00
Roof 1 internal side temperature	47.60	13h30	24.70	07h00
Configuration 1 case internal air temperature	35.70	16h00	27.80	07h00
East wall external side temperature	38.63	14h00	25.26	07h00
East wall internal side temperature	34.28	18h30	28.66	08h00
West wall external side temperature	42.9	15h30	25.24	07h00
West wall internal side temperature	34.86	18h30	28.7	08h00
North wall external side temperature	38.97	16h00	26.11	07h00
North wall internal side temperature	36.63	17h00	27.54	07h30
South wall external side temperature	40.72	14H00	26.26	07h00
South wall internal side temperature	36.55	16H30	26.88	07h00
Floor temperature	32.2	17H00	28.6	07h00
Ambient temperature	43.30	14h00	24.90	07h00

Continued

Building test 2				
	T_{max} (˚C)	T_{max} (h:mm)	T_{min} (˚C)	T_{min} (h:mm)
Roof 2 external side temperature	49.57	13h30	24.99	07h00
Roof 2 internal side temperature	34.40	17h00	28.10	07h00
Configuration 1 case internal air temperature	33.50	17h00	27.90	07h00
East wall external side temperature	38.06	14h00	25.66	07h00
East wall internal side temperature	33.39	19h00	28.61	08h00
West wall external side temperature	44.51	15h30	25.35	07h00
West wall internal side temperature	33.67	19h00	28.7	09h00
North wall external side temperature	38.76	16h00	26.25	07h00
North wall internal side temperature	36.08	17h30	27.37	07h30
South wall external side temperature	40.25	13H30	25.86	07h00
South wall internal side temperature	36.01	16h30	27.19	07h00
Floor temperature	31.8	19h30	29.00	07h00

Figure 5 and Figure 6 show that in sunny weather conditions or cloudy weather conditions, the temperature of the outside face of the sheet metal (roof 1) of the building test 1 remains practically higher during 24 hours than the outside face of the building test 2 roof. This is because during the day, the roof of the building test 1 regularly absorbs part of the sunlight and follows the external thermal variations. However, the temperature of the outside face of the building test 2 roof (proposed roof) is reduced through recovering some of the heat from the sheet all the day by circulating water in the copper tubes under the sheet. During the night, the building test 1 sheet metal is heated by internal heat from the test building rising to the roof by natural convection. In the building test 2, however, the transmission of heat through the roof to the outside is greatly delayed by the insulation layer of plywood and polystyrene. As shown in Figure 5 and Figure 6, the temperature of the inside face of the roof 2 is largely lower than the temperature of the inside face of the roof 1 from 7:30 a.m. to 5:30 p.m. A maximum difference of 15.1˚C between the temperatures of the two inside roof surfaces is recorded in sunny weather condition day and a maximum difference of 15.5˚C in cloudy weather condition day. However, from 5:30 p.m. to 5:30 a.m. the temperature of the inside face of roof 2 slightly higher than the temperature of the inside face of roof 1. This observation was also made in the study of Kurian *et al.* [24]. Indeed, according to these authors, an uninsulated sheet metal roof without a ceiling has lower internal temperatures throughout the night compared to a sheet metal roof with a ceiling or with insulation.

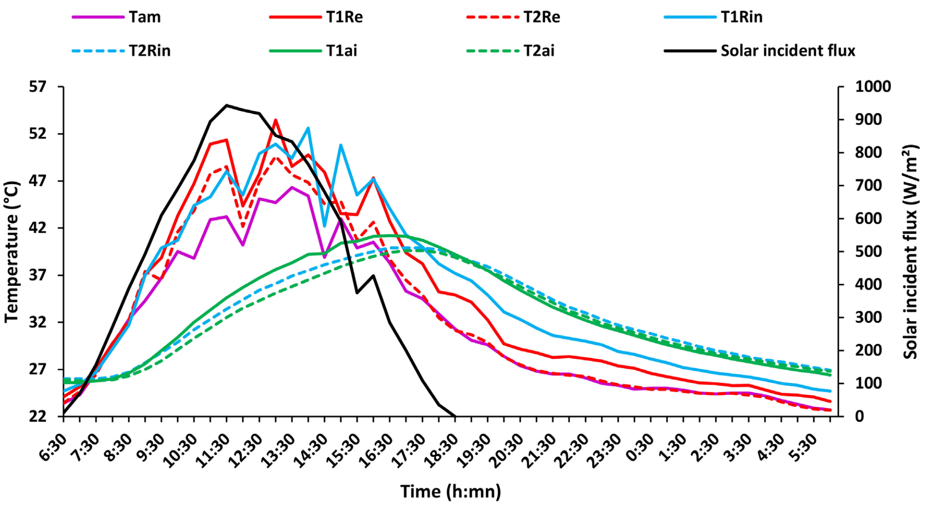


Figure 5. Evolution of outdoor and indoor roofs temperatures, indoor air and ambient air temperature of test configuration 1 versus time (sunny day).

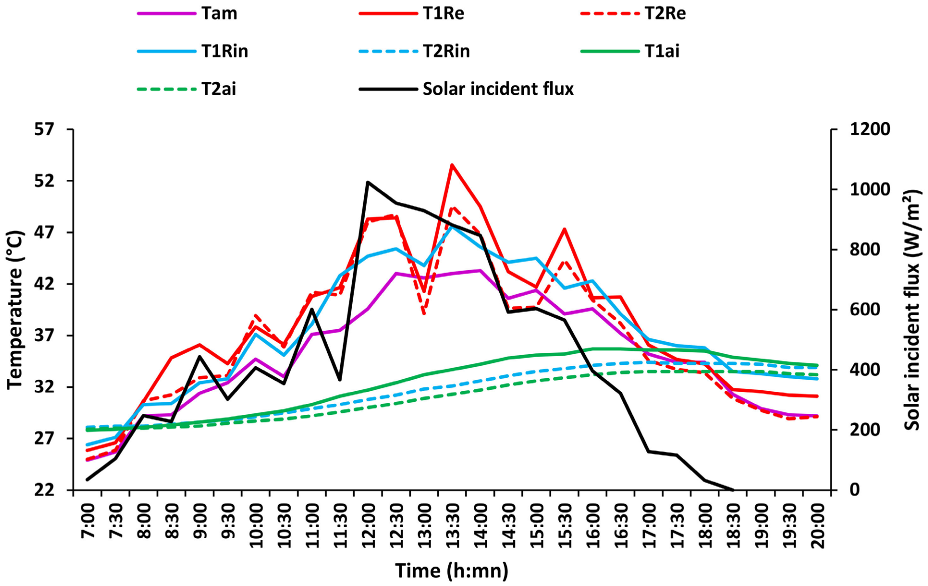


Figure 6. Evolution of outdoor and indoor roofs temperatures, indoor air and ambient air temperature of test configuration 2 versus time (cloudy day).

3.2. Comparison of the Internal Roof Temperatures with the Temperatures of the Other Internal Walls of the Test Buildings

Figure 7 and Figure 8 show that the inside face of the roof 1 for the two experimental configurations is significantly warmer throughout the day with differences of more than on average above 10˚C from 10:00 a.m. to 2:00 p.m. and slightly cooler at night than the other internal walls of the building. This means that the roof 1 transmits heat throughout the day by radiation to all other internal walls. Indeed, according to Cardoso *et al.* [25], in an enclosure, the warmest walls transmit heat by radiation to the lowest walls. Thus, the roof would be primarily responsible for the heat gain inside the SCR test building throughout the day as indicated in the studies of Rawat *et al.* [5] and Kabore *et al.* [1]. However, **Figure 9** and **Figure 10** show that the temperature of the inside face of the roof 2 for the two experimental configurations is lower than the temperatures of the inner walls of the door, window and east wall during the day. Moreover, it is higher than the temperatures of the inner walls of the west and north walls with maximum deviations of less than 3˚C and higher than the floor temperature with a maximum deviation of 6.2˚C. At night, the inside walls of the west, north walls, and the floor become warmer than the internal face of the roof 2, while the internal walls of the door, window and east wall are less warm with deviations of less than 2˚C. This means that roof 2 for the two experimental configurations receives radiant heat from part of the internal walls of the test building during the day and night unlike the case of the roof 1 with transmits radiant heat to the other internal walls all day. Therefore, the walls building 2 contribute to the increase of the indoor air temperature of the building with roof 2. Apart roofs, the internal and external faces of the walls, doors and windows of the two test buildings without east and west wall insulation are practically identical. In the case of walls insulation, the external faces of the walls, doors and windows have practically the same temperatures. However, the internal faces of the insulated walls of the test building with the proposed roof record relatively low temperatures compared with those of the insulated internal walls of the test building with the single sheet roof. This could be due to the heat gain from the inner surfaces of test building 1 through the roof, as opposed to test building 2.

On the other hand, a maximum difference of only 1.1˚C and 0.9˚C (**Figure 5** and **Figure 6**) between the temperature of the inside face of roof 2 and the air temperature in the center of the test building at the warmest hours respectively for test configuration 1 and test configuration 2 is recorded. Furthermore, a maximum difference of only 6.2˚C and 2.8˚C (**Figure 9** and **Figure 10**) between the temperature of the inside face of roof 2 and floor temperature at the warmest hours respectively for test configuration 1 and test configuration 2 is recorded.

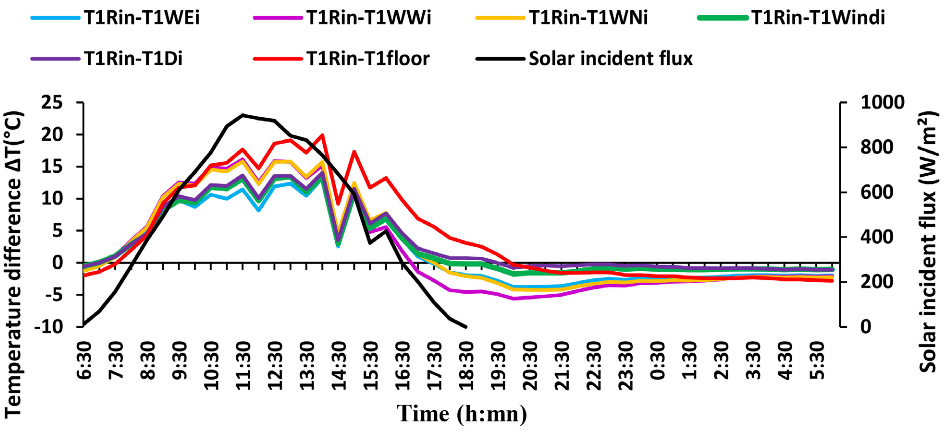


Figure 7. Temperature differences between the inside face of the roof 1 and the other inner walls of configuration 1 building test versus time.

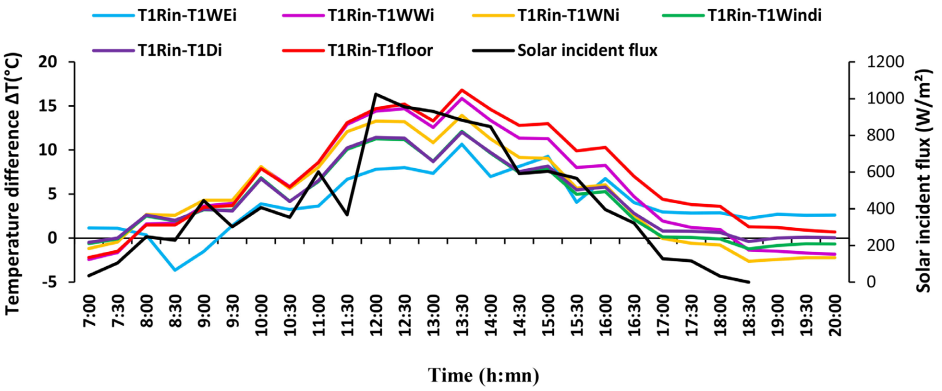


Figure 8. Temperature differences between the inside face of the roof 1 and the other inner walls of configuration 2 building test versus time.

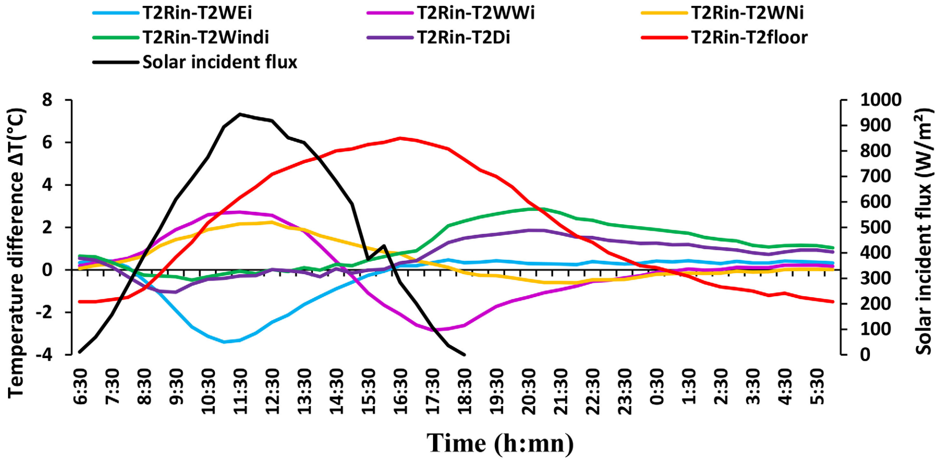


Figure 9. Temperature differences between the inside face of the roof 2 and the other inner walls of configuration 1 building test versus time.

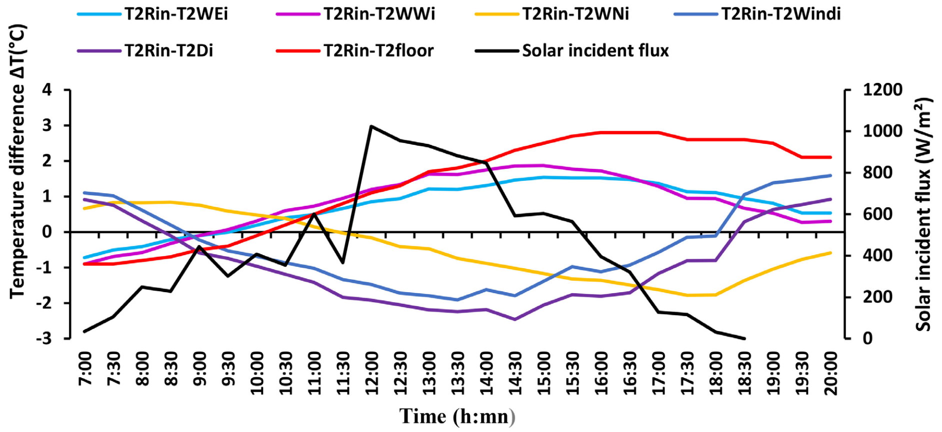


Figure 10. Temperature differences between the inside face of the roof 2 and the other inner walls of configuration 2 building test versus time.

Moreover, a maximum difference of 13.14˚C and 13.9˚C (Figure 5 and Figure 6) between the temperature of the inside face of roof 1 and the air temperature in the center of the test building at the warmest hours respectively for test configuration 1 and test configuration 2 is recorded. Furthermore , a maximum difference of 19.9˚C and 16.8˚C (**Figure 7** and **Figure 8**) between the temperature of the inside face of roof 1 and floor temperature at the warmest hours respectively for test configuration 1 and test configuration 2 is recorded. So, the use of roof 2 (proposed roof) creates a pleasant atmosphere inside the building unlike the roof made of simple sheet metal. In Fact, the large vertical variations in temperature from the inner roof surface to the floor within building test 1 imply a more accelerated and larger heat exchange process between the roof and the indoor environment [25]. This causes discomfort due to high radiant heat exchange regardless of the physical environment.

3.3. Time Lag and Decrement Factor Calculation

The values of the time lag and decrement factor of the different roofs for the two considered configurations are summarised in **Table 4**. The calculated values show that for the considered configurations the proposed roof has a time lag of 3.5 hours with relatively low decrement factors of 0.51 and 0.25 for configurations 1 and 2 respectively. On the other hand, the roof constructed with a simple metal sheet records a zero time lag when the east and west walls of the building are insulated and when the walls are not insulated. In addition, the insulation of the east and west walls results in smaller decrement factors. The values of the time lag and decrement factors for roof 2 show that the proposed roofing system can significantly delay the transmission of heat received through the roof to the interior of the building. It is therefore suitable for hot climates where climatic variations are often critical.

Table 4. Time lag and decrement factor values.

Configuration	Building side		Time lag Φ (h:mn)	Decrement factor f
Configuration 1	Roof	Building test 1	0	0.87
		Building test 2	3h30	0.51
	East wall	Building test 1	5h30	0.85
		Building test 2	5h30	0.79
	West wall	Building test 1	1h30	0.75
		Building test 2	1h30	0 .76
	North wall	Building test 1	1h30	0.91
		Building test 2	1h30	0.90
	South wall (Door)	Building test 1	2h00	0.67
		Building test 2	2h30	0.61
Configuration 2	Roof	Building test 1	0	0.73
		Building test 2	3h30	0.25
	East wall	Building test 1	4h30	0.42
		Building test 2	5h00	0.38

Continued

West wall	Building test 1	03h00	0.35
	Building test 2	03h30	0.26
North Wall	Building test 1	01h00	0.71
	Building test 2	01H30	0.70
South wall (Door)	Building test 1	02h30	0.67
	Building test 2	03h00	0.61

3.4. Assessment of Ambient Humidity and Building Test Humidity

Figure 11 and Figure 12 show that the relative humidity within the RCR test building is almost uniform compared to the relative humidity within the SCR test building. However, the relative humidity in the RCR test building remains the highest compared to the SCR test building throughout the experiments as reported in the study by Ponni *et al.* [20].

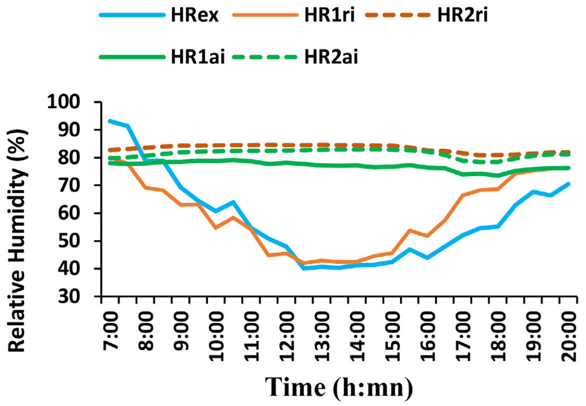


Figure 11. Relative humidity of the ambient air, the inner roof surface and the air in the center of the roof of configuration 2 versus time.

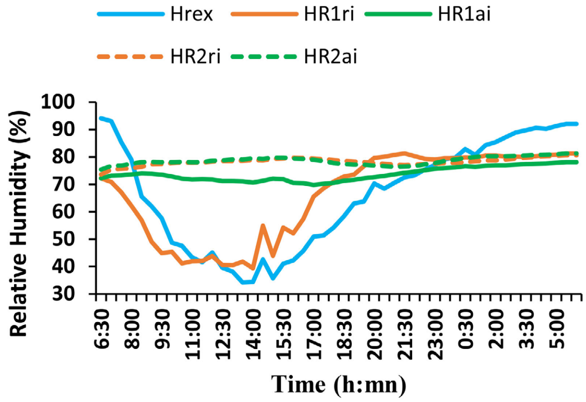


Figure 12. Relative humidity of the ambient air, the inner roof surface and the air in the center of the roof of configuration 1 versus time.

3.5. Assessment of the Temperature of the Hot Water Produced

During the day, an average amount of about 60 L of hot water was produced and discharged regularly into the barrel from 7:00 a.m. to 6:30 p.m. Following the heating of the water in the 30 meters long supply pipe upstream of the roof, the water temperature at the collector inlet varied from 23.42˚C to 35.52˚C, the temperature of the water leaving the collector after heat recovery varied from 23.46˚C to 42.5˚C and the tank water varied form 25.89˚C to 39.35˚C in sunny weather day (**Figure 13**). The water temperature at the collector inlet varied from 24.15˚C to 35.9˚C and the temperature of the water leaving the collector after heat recovery varied from 24.55˚C to 38.88˚C and the tank water varied from 26.80˚C to 38.53˚C in cloudy weather day (**Figure 14**).

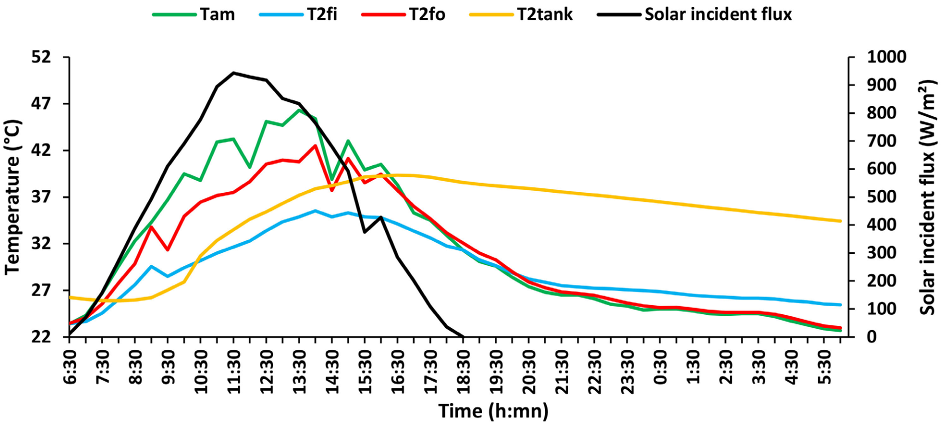


Figure 13. Variation of inlet, outlet and barrel temperatures versus time in sunny weather day.

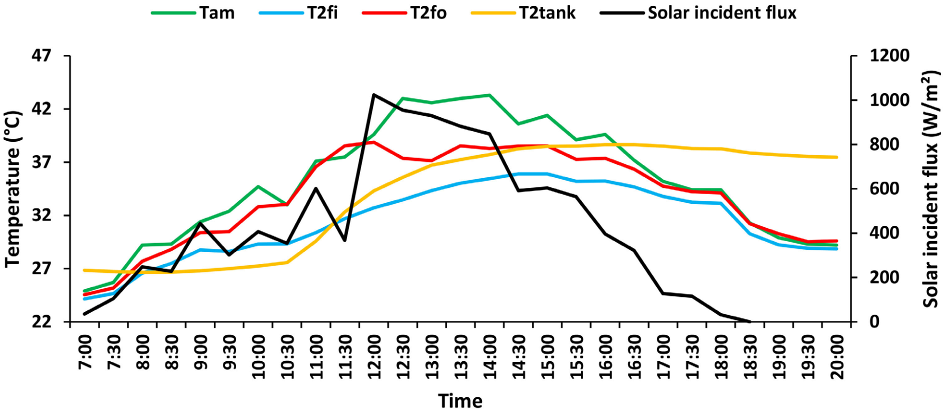


Figure 14. Variation of inlet, outlet and barrel temperatures versus time in cloudy weather day.

4. Conclusion

This experimental study has evaluated the interior heat gain reduction capacity of a corrugated heat recovery roof compared to a single sheet corrugated roof. The recovered heat was used to produce domestic hot water. The study showed that the use of the corrugated heat recovery roof provided relatively uniform indoor temperatures and relative humidities throughout the day; whereas the single corrugated sheet house provided a higher and highly stratified indoor temperature from the inside of the roof to the floor throughout the day. A difference of more than 15˚C between the temperature of the inner side of proposed roof and the roof temperature of the single metal roof at the warmest hours. A quantity of about 60 Liters of hot water with a maximum temperature of 39.35˚C was produced throughout the sunny weather day and a maximum temperature of 38.53˚C on a cloudy weather day. Thus, this study could be an alternative solution for improving the thermal capacities of sheet metal roofs in order to reduce excessive energy consumption for maintaining internal temperatures that are quite pleasant enough for the occupants in the homes. In addition, it could contribute to the reduction of the use of fossil fuels for hot water production in households. The contribution of the walls of the test buildings to the temperature gain inside was significant during this experimental study. Therefore, to better assess the impact of this roof on indoor comfort, a study with the insulation of the walls of the test houses would be desirable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Kabore, M. (2014) Assessment on Passive Cooling Techniques to Improve Steel Roof Thermal Performance in Hot Tropical Climate. *International Journal of Energy and Power Engineering*, **3**, 287-295. https://doi.org/10.11648/j.ijepe.20140306.12

[2] Fasogbon, S.K., Wahaab, A.B. and Oyewola, M.O. (2015) Thermal Comfort Characteristics of Some Selected Building Materials in the Regional Setting of Ile-Ife, Nigeria. *Journal of Natural Resources and Development*, **5**, 54-58. https://doi.org/10.5027/jnrd.v5i0.07

[3] Sako, M.K., N'guessan, Y., Gbaha, P., N'guessan, K. and Kouadio, M.K. (2006) Bio-Climatic Design of the Habitat in Tropical Climate: Case of Côte D'Ivoire. *Global Journal of Pure and Applied Sciences*, **12**, 553-558.

[4] Krüger, E.L., Harimi, D., Harimi, M., Kurian, J. and Ideris, Z. (2005) Assessment of Thermal Performance of Roof System with Galvanized Steel in East Malaysia. *PLEA*2005—*The* 22*nd Conference on Passive and Low Energy Architecture*, Beirut, 13-16 November 2005, 395-399. https://www.researchgate.net/publication/301731653

[5] Rawat, M. and Singh, R.N. (2022) A Study on the Comparative Review of Cool Roof Thermal Performance in Various Regions. *Energy and Built Environment*, **3**, 327-347. https://doi.org/10.1016/j.enbenv.2021.03.001

[6] Yaccoubi, M.I., Mydin, M.A.O. and Md Sani, N. (2014) Appraisal on Roofing Materials Thermal Properties in Malaysian Climate. *Elixir International Journal*, *Elixir Civil Engineering*, **68**, 22342-22345.

[7] Omar, A.I., Virgone, J., Vergnault, E., David, D. and Idriss, A.I. (2017) Energy Saving Potential with a Double-Skin Roof Ventilated by Natural Convection in Djibouti. *Energy Procedia*, **140**, 361-373. https://doi.org/10.1016/j.egypro.2017.11.149

[8] Joshi, V. (2020) Heat Transfer Characterization of Test Rooms with Six Different Roofs. *International Journal of Heat and Technology*, **38**, 131-136. https://doi.org/10.18280/ijht.380114

[9] Narwaria, U.S., Singh, M., Verma, K.K. and Bharti, P.K. (2017) Amelioration of Thermal Stress Using Modified Roof in Dairy Animals under Tropics: A Review. *Journal of Animal Research*, **7**, 801-812. https://doi.org/10.5958/2277-940x.2017.00124.3

[10] Yazdani, A.R. and Gupta, L.R. (2000) Effect of Housing and Feeding System on Feed Utilization and Physiological Responses in Crossbred Calves. *Indian Journal of Dairy Science*, **53**, 88-92.

[11] Hashemi, A., Cruickshank, H. and Cheshmehzangi, A. (2015) Improving Thermal Comfort in Low-Income Tropical Housing: The Case of Uganda. *ZEMCH* 2015, *International Conference*, Lecce, 22-25 September 2015, 1-11.

[12] Adounkpe, J.G., Lawin, A.E., Ahouannou, C., Akiyo, R.O.L. and Sinsin, B.A. (2013) Modeling Solar Energy Transfer through Roof Material in Africa Sub-Saharan Regions. *ISRN Renewable Energy*, **2013**, Article ID: 480137. https://doi.org/10.1155/2013/480137

[13] Torres-Quezada, J., Coch, H. and Isalgué, A. (2019) Assessment of the Reflectivity and Emissivity Impact on Light Metal Roofs Thermal Behaviour, in Warm and Humid Climate. *Energy and Buildings*, **188**, 200-208. https://doi.org/10.1016/j.enbuild.2019.02.022

[14] Harimi, M., Harimi, D., Kurian, V.J. and Bolong, N. (2006) Evaluation of the Thermal Performance of Metal Roofing under Tropical Climatic Conditions. *Malaysian Construction Research Journal*, **1**, 41-51.

[15] Geron, L. (2007) Enhanced Summertime Comfort for Steel Building by Means of an Innovative Ventilated Double Skinner Roofing System: Presentation of a Prototype Experiment. *Revue de Métallurgie*, **104**, 203-208. https://doi.org/10.1051/metal:2007149

[16] Li, H. and Tong, S. (2016) Natural Convective Heat Transfer in the Inclined Rectangular Cavities with Low Width-to-Height Ratios. *International Journal of Heat and Mass Transfer*, **93**, 398-407. https://doi.org/10.1016/j.ijheatmasstransfer.2015.10.027

[17] Hashemi, A. (2017) Effects of Thermal Insulation on Thermal Comfort in Low-Income Tropical Housing. *Energy Procedia*, **134**, 815-824. https://doi.org/10.1016/j.egypro.2017.09.535

[18] Robelison, S. and Lips, B. (2010) Influence thermique de l'emplacement du toit en chaume sous le toit en tôle d'un habitat à Antananarivo-Madagascar. *Afrique Science: Revue Internationale des Sciences et Technologie*, **4**, 318-338. https://doi.org/10.4314/afsci.v4i3.61693

[19] Yew, M.C., Ramli Sulong, N.H., Chong, W.T., Poh, S.C., Ang, B.C. and Tan, K.H. (2013) Integration of Thermal Insulation Coating and Moving-Air-Cavity in a Cool Roof System for Attic Temperature Reduction. *Energy Conversion and Management*, **75**, 241-248. https://doi.org/10.1016/j.enconman.2013.06.024

[20] Ponni, M.M. and Baskar, D.R. (2015) Comparative Study of Different Types of Roof and Indoor Temperatures in Tropical Climate. *International Journal of Engineering and Technology*, **7**, 530-536.

[21] Wang, Y. and Fukuda, H. (2016) Timber Chips as the Insulation Material for Energy Saving in Prefabricated Offices. *Sustainability*, **8**, Article 587. https://doi.org/10.3390/su8060587

[22] Blaise, K.K., Magloire, K.E.P. and Prosper, G. (2018) Thermal Performance Amelioration of Flat Plate Solar Collector of an Indirect Dryer. *Mathematical Modelling of Engineering Problems*, **5**, 341-347. https://doi.org/10.18280/mmep.050410

[23] Koffi Fernandez, T. (2018) Study of a Bioclimatic Building in Wet Tropical Zone: Application of the Study of the Thermal Behavior of a Building in Cote D'ivoire. *International Journal of Sustainable and Green Energy*, **7**, 7-15. https://doi.org/10.11648/j.ijrse.20180702.11

[24] Ozel, M., and Ozel, C. (2012) Effects of Wall Orientation and Thermal Insulation on Time Lag and Decrement Factor. 9*th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, Malta, 16-18 July 2012, 680-684.

[25] Oktay, H., Yumruta, R., Zerrakki Istk, M. and Aydin, H. (2018) The Influence of Building Design Parameters on the Time Lag and Decrement Factor. *International Engineering and Natural Sciences Conference* (*IENSC*, 2018), Turkey, 14-17 November 2018, 1121-1131.

[26] Netam, N., Sanyal, S. and Bhowmick, S. (2020) A Mathematical Model Featuring Time Lag and Decrement Factor to Assess Indoor Thermal Conditions in Low-Income-Group House. *Journal of Thermal Engineering*, **6**, 114-127. https://doi.org/10.18186/thermal.728054