

Internal Microclimate: Service Life Assessment for a Building attached with a Solar Chimney-Collector

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Abstract

The use of a solar chimney-collector enhances natural ventilation and passive cooling strategies of buildings thus helps in reducing energy use, CO₂ emission and pollution in general. The aim of this paper, therefore, is to obtain service life of a solar chimney-collector gadget attached to a specimen room to realize natural ventilation. The room was made of glass which conditioned it to a remarkable heat, while the solar chimney comprised of insulated wooden box, a vent pipe and an inlet opening with its cover made of the solar collector (a flat box of photovoltaic glass cap, optically coated aluminium absorber and a serpentine tube). Results of a five week internal microclimatic conditions measurement, each for solar chimney and the specimen room with all windows opened and all windows closed, show that a test-retest reliability analysis of 0.745 and 0.711 were obtained respectively, while the average life-time failure probability of 0.266 was predicted, the chimney-collector system will serve for 50 years.

Keywords: Energy, solar collector, chimney, reliability, service life

1. Introduction

Two types of natural ventilation may occur in buildings: wind driven ventilation and stack ventilation. The pressures generated by buoyancy or 'the stack effect', are quite low with typical values ranging between 0.3 to 3.0Pa, while wind pressures are usually far greater and are between 1.0 to 35Pa. The majority of buildings will rely mostly on the wind driven ventilation while stack ventilation may have several benefits. The most efficient design for a natural ventilation of a building should implement both types of ventilation. The total installed capacity of solar hot water systems is approximately 154 GW (Bradford, 2006).

China is the world leader in their deployment of solar hot water system with 70 GW installed as of 2006 and a long term goal of 210 GW by 2020. Israel and Cypress are the per capita leaders in the use of solar hot water systems with over 90% of homes using them. In the United States, Canada and Australia, heating swimming pools is the dominant application of solar hot water with an installed capacity of 18 GW as of 2005. In the United States (Bradford, 2006), heating, ventilation and air conditioning (HVAC) systems account for 30% of attaining the energy used in commercial buildings and nearly 50% of the energy used in the residential buildings. Solar heating, cooling and ventilation technologies can be used to offset a portion of this energy.

2. Ventilation

2.1 Natural ventilation

This natural ventilation process can be augmented by a solar chimney (Bansal et al., 1993). The chimney has to be higher than the roof level, and be constructed on the wall facing the direction of the sun. Absorption of heat from the sun can be increased by using a glazed surface on the side facing the sun. Heat absorbing material can be used on the opposite side. The size of the heat-absorbing surface is more important than the diameter of the chimney. A large surface area allows for more effective heat exchange with the air necessary for heating by solar radiation. Heating of the air within the chimney will enhance convection, and hence airflow through the chimney. Openings of the vents in the chimney should face away from the direction of the prevailing wind.

The added advantage of the design is that the system may be reversed during the cold season, providing heating instead. Accordingly, the use of a solar chimney may benefit natural ventilation and passive cooling strategies of buildings thus help to reduce energy use, CO₂ emissions and pollution in general (Ogunrinde, 1998). Some of the potential benefits regarding natural ventilation and use of solar chimneys are:

- Improved ventilation rates on still, hot days
- Reduced reliance on wind and wind driven ventilation

- Improved control of air flow through a building
- Greater choice of air intake (i.e. leeward side of building)
- Improved air quality and reduced noise levels in urban areas
- Increased night time ventilation rates
- Allowed ventilation of narrow, small spaces with minimal exposure to external elements
- Improved passive cooling during warm season (mostly on still, hot days)
- Improved night cooling rates
- Enhanced performance of thermal mass (cooling, cool storage)
- Improved thermal comfort (improved air flow control, reduced draughts)

Ogunrinde (1998) confirmed that natural ventilation can also be described as the process of supplying and removing air through an indoor space by natural means. There are two types of natural ventilation occurring in buildings: wind driven ventilation and stack ventilation. The latter is described in the following section.

2.2 Stack driven ventilation

In the works of Dai et al (2003), a stack effect is shown to be temperature induced. When there is a temperature difference between two adjoining volumes of air the warmer air will have lower density and be more buoyant thus will rise above the cold air creating an upward air stream. Forced stack effect in a building takes place in a traditional fire place. Passive stack ventilators are common in most bathrooms and other type of spaces without direct access to the outdoors.

In order for a building to be ventilated adequately via stack effect the inside and outside temperatures must be different so that warmer indoor air rises and escapes the building at higher apertures, while colder, denser air from the exterior enters the building through lower level openings. Stack effect increases with greater temperature difference and increased height between the higher and lower apertures. The neutral plane in a building occurs at the location between the high and low openings at which the internal pressure will be the same as the external pressure (in the absence of wind). Above the neutral plane, the air pressure will be positive and air will rise. Below the neutral plane the air pressure will be negative and external air will be drawn into the space. Stack driven ventilation has several significant benefits as it:

- Does not rely on wind and can take place on still, hot summer days when it is most needed
- Natural occurring force (hot air rises)
- Relatively stable air flow (compared to wind)
- Greater control in choosing areas of air intake
- Sustainable method

Some limitations of stack driven ventilation include:

- Lower magnitude compared to wind ventilation
- Relies on temperature differences (inside/outside)
- Design restrictions (height, location of apertures) and may incur extra costs (ventilator stacks, taller spaces).

This technique can be implemented in a home by designing an exit window (or other openings) that draws warm air out of the top of the building/room and another window/vent/opening in a lower level of the building where cool air could enter. The scheme in Figure 1 illustrates the process as expressed by Balcomb (1992).

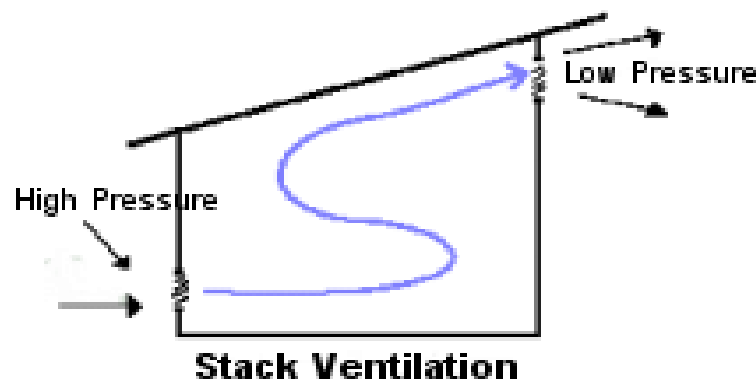


Figure 1. Convective stack ventilation movement.

3. Estimation of Stack Effect Ventilation

The natural ventilation flow rate can be estimated with this equation:

$$Q_S = C_d A \sqrt{2 g H_d \frac{T_I - T_O}{T_I}} \quad (1)$$

Where: Q_S = stack vent airflow rate, A = cross-sectional area of opening (assumes equal area for inlet and outlet), C_d = discharge coefficient for opening, g = gravitational acceleration (9.807m/s), H_d = height from midpoint of lower opening to neutral pressure level (NPL), NPL = location in the building envelope with no pressure difference between inside and outside, T_I = average indoor temperature between the inlet and the outlet and T_O = outdoor temperature.

The main aim of this work is to construct, estimate the service life and prepare the cost analysis of a solar chimney-collector used for enhancing ventilation in a room. Data were obtained for materials and their properties for the construction of the solar chimney-collector.

4. Solar Thermal Collector

4.1 Common Types of Solar Collector

There are many flat-plate collector designs, but generally all of them consist of a flat-plate absorber, which intercepts and absorbs the solar energy, a transparent cover(s) that allows solar energy to pass through but reduces heat loss from the absorber, a heat-transport fluid (air, antifreeze or water) flowing through tubes to remove heat from the absorber and a heat insulating backing. One flat plate collector is designed to be evacuated in order to prevent heat loss. The first accurate model of flat plate solar collectors was developed by Hottel and Whillier (1955).

4.2 Solar Chimney Collector

A solar chimney-collector — often referred to as a thermal chimney-collector — is a way of improving the natural ventilation of buildings by using convection of air heated by passive solar energy. A simple description of a solar chimney is that of a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building.

During the day solar energy heats the chimney and the air within it, creating an updraft of air in the chimney. The suction created at the chimney's base can be used to ventilate and cool the building below. In most parts of the world it is easier to harness wind power for such ventilation, but on hot windless days a solar chimney can provide ventilation where otherwise there would be none.

Solar chimney can serve many purposes. Direct gain warms air inside the chimney causing it to rise out of the top and drawing air in from the bottom. This drawing of air can be used to ventilate a home or office, to draw air through a geothermal heat exchange, or to ventilate only a specific area such as a composting toilet (Afonso and Oliveira, 2000).

5. Methodology and Materials

The major building materials used for the construction of the model building specimen with the solar chimney include: pyrex glass was used for the model building specimen, aluminum roofing sheet, ply wood (used as an insulator), transparent glass, aluminium metal sheet (coated black) and the pipe (used as air outlet). Also the major tools used during the construction of the model building specimen includes: Chloroform (trichloromethane) and araldite (both were used mainly as adhesive materials). Figure 2 shows the section of a solar collector. The absorber (aluminium) is fixed in the same frame and directly below the plain glass. The absorber is coated with black paint.

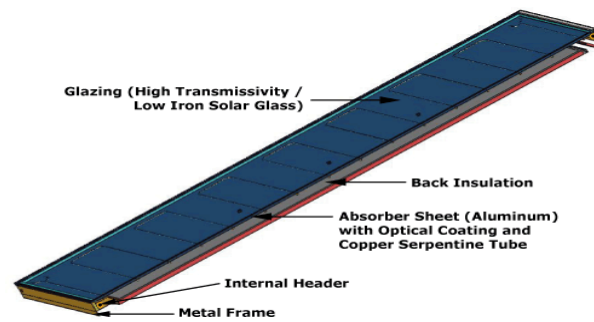


Figure 2 Solar collector

5.1 The solar chimney-collector system

Applying (Bansal et al. 1993, Olayioye (2003) numerical calculations applied for different values of ambient temperature and solar radiation, it has been shown that a solar collector area of $2.25(\text{m}^2)$ is able to induce an air flow between $140(\text{m}^3/\text{hr})$ and $330(\text{m}^3/\text{hr})$ for solar radiation of $200(\text{W}/\text{m}^2)$ and $1000(\text{W}/\text{m}^2)$ respectively.

In this work, size of the model chimney = $350\text{mm} \times 321\text{mm} \times 150\text{mm}$. The plain glass has reflectivity of 0.9 and placed in the same frame with absorber sheet (aluminium) painted black. Table 1 shows the properties of the materials used. The plain glass has a good resistance to rapid temperature variation (thermal shock).

Table 1 Properties of plain glass and absorber

Materials	Specific heat ($\text{kJ}/\text{kg}^\circ\text{C}$)	Density $\text{P}(\text{kg}/\text{m}^3)$	Reflectivity	Absorbivity
Glass (Plain glass)	1.1	2200	0.9	
Aluminium (absorber)	0.88	2.7	-	0.78

Source: Olayioye (2003)

The construction methods for the model room installed with the solar chimney collector are shown in Figures 3 to 5.



Figure 3 Specimen building under construction



Figure 4 Marking out the roofing sheet



Figure 5 Model building with the attached solar chimney-collector

5.2. Temperature measurement

The average temperatures were measured, using digital multi-meters for the ambient, room and chimney for the two conditions (i.e. for window closed and window opened) for 5 weeks and between 10.00 Hrs to 15.00 Hrs each day for window closed and window opened. The average weekly reports are shown in Tables 2 and 3.

Table 2 Average weekly temperature for the Ambient, room, and chimney for the two windows closed

Week	Ambient Temperature		Room Temperature		Chimney without collector		Chimney with collector		Room R.H (%)
	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	
1	35.2	21.4	30.0	22.4	30	22.5	35.5	22.1	40.3
2	33.3	21.1	30.2	22.4	31	22.2	37.2	22.4	38.8
3	32.7	21.8	30.2	22.1	30	22.5	39.8	21.6	33.8
4	33.5	21.4	33.3	21.2	34	21.1	39.2	21.9	32.8
5	34.5	21.7	32.8	21.2	36	22.7	39.8	21.5	33.8

Table 3 Average weekly temperature for the ambient, room, chimney for the two windows opened

Week	Ambient Temperature		Room Temperature		Chimney without collector		Chimney with collector		Room R.H %
	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	<u>Dry</u>	<u>Wet</u>	
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	
1	36.5	23.3	29.0	18.2	27	16	35.2	22.0	31.25
2	29.0	18.9	26.0	18.8	28	19	31.8	17.4	37.75
3	32.7	21.8	30.2	22.1	28	19	39.8	21.6	33.25
4	34.2	19.8	30.3	19.4	33	19	32.6	21.1	32.25
5	35.2	22.0	27.0	19.0	35	20	40.3	21.7	37

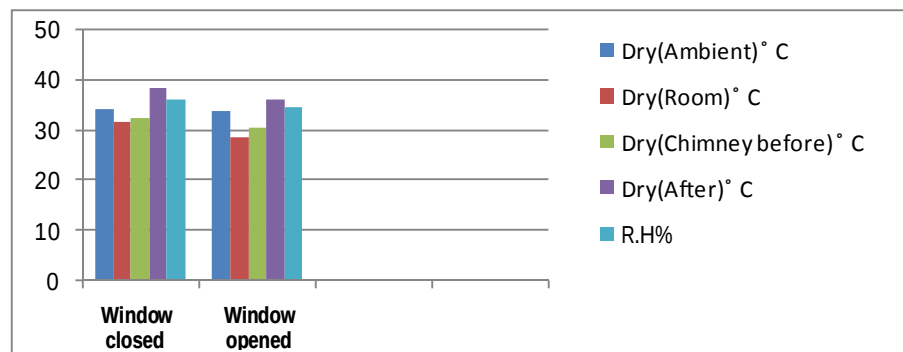


Figure 6 Average temperature and relative to humidity of the ambient, room and chimney

5.3 Reliability techniques and application

Constant failure rate (CFR) is employed here for easy algebraic manipulation (Cho et al, 2007, Ogunrinde, 1998).

$$R(t) = e^{-dt} \quad (2)$$

Where, $R(t)$ = total temperature in a week, $d_i = \frac{T_{Av(i)}}{R_{i-1}}$ is ratio of average temperature to total temperature and t = time (week), and T_{av} = average temperature. The failure density is expressed with respect to constant rate of failure as:

$$F(t) = de^{-dt} \quad (3)$$

So that the estimator is expressed as recommended by Leitch (1998):

$$F(t) = 1 - e^{-dt} \quad (4)$$

The mean time to failure (MTTF) is the average functioning (without a failure) period for an item or average life cycle of a number of items, and it is expressed as:

$$MTTF = 1/d \quad (5)$$

To determine the reliability;

$$R = e^{-t/m} \quad (6)$$

where t = period of time, d = temperature intensity/week, m = expected average numbers of break down = 2 (assuming that all other parts of the solar collector remain stable except glass and black painted aluminium that may break due to a dynamic force and colour faint respectively). Average temperatures intensity/week, for room with window closed only, are shown in Table 4.

Table 4 Average temperature /week (window closed)

Week	Average temperature (T_{av}) °C		Energy (Q) W		Temperature intensity (R_i) %		Rate per week (d)	
	RT	CT	R	C	R	C	R	C
1	32	37	92.93	98.56	51.1	20	0.63	1.86
2	33	40	118.27	76.03	61.0	18.5	0.54	2.16
3	32	34	185.86	25.34	55.9	13.2	0.57	2.57
4	34	41	123.90	38.11	36.7	10.2	0.92	3.9
5	32	36	98.56	74.62	37.0	12.0	0.86	3.00

RT, CT = Room and Chimney temperatures respectively

5.4 Optimum Design Based on Service Life Cost

Minimum material cost may not be the most essential characteristics for the utility of a structural component. If failure consequence is taken into account, the general criteria for the design of the solar chimney-collector produce the minimum total expected cost were considered here: (a) initial expected cost $C_i(t)$ and (b) expected failure during life-time (cost due to damage of collector glass and colour faint on aluminium) This is necessary to introduce lifetime failure probability P_{life} in the objective function which is minimized as,

$$C_{life.min} = C_i(t) + C_{cf} = C_i(t) + C_f P_{life} \quad (7)$$

$$\text{In which:} \quad P_{life} = 1 - \phi(R(t)) \quad (8)$$

$$\text{And} \quad C_f = 1.0C_m \quad (9)$$

where C_m = cost of materials which are damaged (glass) and colour faint (black soot on aluminium) during the service life of the solar chimney-collector is 2USD (300 Nigeria Naira in June, 2009).

5.5 Specification of Reliability

It has been necessary to specify not only for the performance characteristics of the Earth wall at early stage but also the reliability and its allowable characteristics. A realistic reliability figure at this stage must be determined for the solar collector life span. In this paper, a design approach was based on early work of Frangopol and Hendawi (1994). Considering the Reliability Panel Diagram (RPD) as shown in Figure 7, the reliability of the solar collector components are indicated. This assumption was used to determine the wall total cost factor (K_c) in equation (12) (Environmental Protection Agency, EPA, 2007).

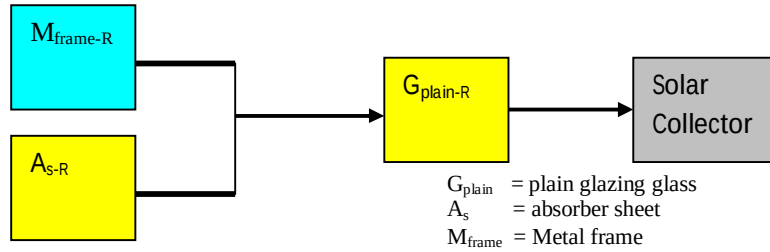


Figure 7 Block diagram analysis for solar collector

Table 5 shows the reliability of panel, mortar, plaster and wall with time. At this stage a reliability figure must be determined for wall life span. In this paper, a design approach used is based on the early work of Cho (2007), Frangopol and Hendawi (1994).

Table 5 Reliability of brick, mortar, plaster and wall with time

$M_{\text{frame-R}}$	Time (year)	$A_{\text{s-R}}$	Time (year)	$G_{\text{plain-R}}$	Time (year)	$S_{\text{C-R}}$	Time (year)
0.96	123	0.93	48	0.93	40	0.87	68
0.45	146	0.89	76	0.97	65	0.65	95
0.70	178	0.85	106	0.87	91	0.56	95
0.69	215	0.81	138	0.83	122	0.45	192
0.66	252	0.77	156	0.79	154	0.44	192
0.67	292	0.73	202	0.75	188	0.36	230
0.62	335	0.71	243	0.71	224	0.31	270

$M_{\text{frame-R}}$ = Metal frame reliability, $A_{\text{s-R}}$ = Absorber sheet reliability,
 $G_{\text{plain-R}}$ = Plain Glass reliability, $S_{\text{C-R}}$ = Solar Collector reliability

6. Estimation of Capacity Loss of Surface Area

The effectiveness of the collector loaded with the sun intensity depends mainly on its total surface area. For a uniform loading, the failed area as a function of time t , is expressed as:

$$A(t) = L \times B \quad (10)$$

(intact or undamaged for $t \leq T$)

$$\text{and} \quad A(t) = L [B - d_r(t - T)] \quad (11)$$

(damaged section, for $t > T$)

where L , B = length, breadth of collector surface area respectively, T = time of service initiation, d_r = rate of damage of plain glass (broken) and faint or scratched surface area of absorber.

The loss of material due to deterioration under constant load is time-dependent. Consider the solar collector, the reliability-based optimum design of this wall requires a definition of the 5 design variables and 3 parameters as shown in Table 6. The objective of the optimization process is to minimize the total cost of the collector with the factor:

$$K_c = \frac{C_{G - \text{plain}}}{C_{M - \text{frame}} + C_{A - s}} \quad (12)$$

where $C_{M - \text{frame}}$, $C_{A - s}$ and $C_{p - \text{glass}}$ = cost of metal frame, absorber and plain glass respectively, the value of K_c = 0.10.

Table 6. Design variables (V) and design parameters (P) for RR100 building

Notation	Variables	Units
V1	Metal frame length, $L_{M-frame}$	1000mm
V2	Metal thickness, $T_{M-frame}$	0.45mm
V3	Metal breadth, $B_{M-frame}$	600mm
V4	Plain glass thickness, $T_{G-plain}$	0.10mm
V5	Absorber sheet thickness, T_{A-S}	0.25mm
P1	Sun intensity, I_s	725 W/m ²
P2	Reflectivity of plain Glass	0.9
P3	Absorptivity of aluminium	0.78

The residual capacity factor due to loss of surface areas of the plain glass and the absorber is expressed as,

$$A_{CR} = \frac{A_{damaged}}{A_{undamaged}} \quad (13)$$

And the total surface area loss

$$A_{loss} = A_{undamaged} - A_{damaged} \quad (14)$$

where $A_{damaged}$ is the surface area remained due to formation of cracks of the plain glass and $A_{undamaged}$ is undamaged surface area of the glass, while the residual capacity factor due to loss of efficiency of the solar collector:

$$R_{CF} = \frac{E_{damaged}}{E_{undamaged}} \quad (15)$$

where E_{intact} is the equivalent solar collector at the highest efficiency (the measure of the effectiveness with which the system performs, which is also the ratio of a system's work output to its work input). $E_{damaged}$ = efficiency of the system due damage of the collector's surface area. And the loss of efficiency is expressed as:

$$E_{loss} = E_{undamaged} - E_{damage} \quad (16)$$

7. Discussion of the Results

7.1 Efficiency and loss of surface area

In Table 7, the results of the surface area and efficiency of the solar collector were shown, while Figures 8 and 9 show relationship between the residual capacity factor and loss. As the surface area increases the residual capacity factor remains at maximum value of 0.98, while the residual capacity factor is nonlinear as the loss in efficiency

Table 7 Loss of collector surface area and its equivalent efficiency

$A_{undamaged}$ mm ²	$A_{damaged}$ mm ²	$E_{undamaged}$	$E_{damaged}$	E_{loss}
112350	111226.9	1.0	0.98	0.99
112350	110103.0	1.0	0.96	0.98
112350	108979.5	1.0	0.94	0.97
112350	107856.0	1.0	0.92	0.96
112350	101115.0	1.0	0.81	0.90
112350	89880.0	1.0	0.64	0.80
112350	56175.0	1.0	0.25	0.50

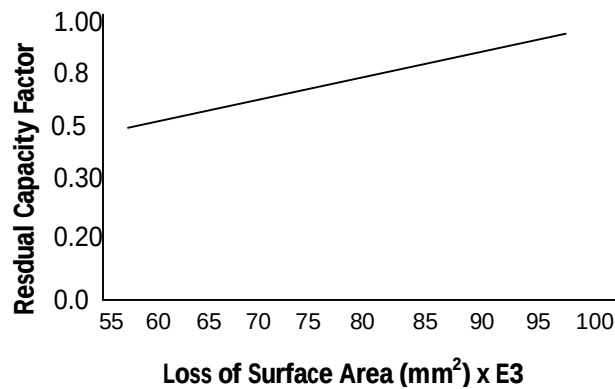


Figure 8 Residual capacity factor and area loss

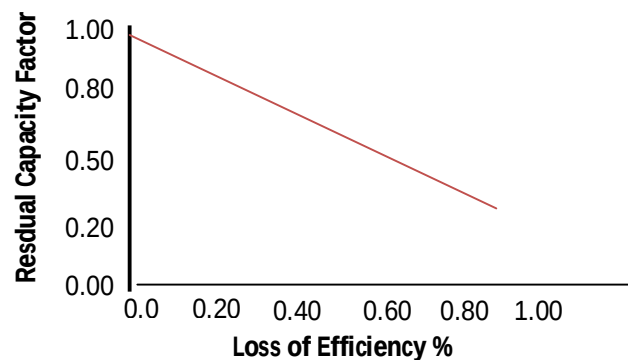


Figure 9 Residual capacity factor vs loss of efficiency.

8. Results of Analysis and Discussion

8.1 Cost analysis

The cost of constructing a standard room size of 3.6m x 3.6m x 3.0m, using pyrex glass for the wall with the solar chimney-collector, is 2,490.65 USD (373,598.00 Nigeria Naira), and when the cost was projected for the same room size using sandcrete blocks with a solar chimney-collector attached to it, the cost of construction is 14,754.18 USD (2, 213,127.00 Nigeria Naira).

8.2 Reliability analysis

Results of the analysis showed **that**, for a closed window room, the MTTF of 0.303, the average Reliability = 0.746, while the reliability of 0.711 was recorded for a room with window opened having a lifetime failure probability $P_{life} = 0.288$. The measured relative humidity (RH) ranges between 31.20 and 37.75% These values fall within the relative humidity recommended for houses by U.S Environmental Protection Agency. Homes that have high humidity levels are more likely to become infested with termites and carpenter-ants since these insects prefer such condition and migrate towards moist wood, and the steel components of a home may begin to rust if the indoor relative humidity is too high. At the reliability of 0.746 for $P_{life} = 0.254$, service life of the solar chimney-collector is estimated to be 50 **years**.

7. Conclusion

From the measurement of the room temperature, it was observed that the relative humidity levels in the air changes drastically due to the heating and cooling processes. These processes lead to extreme wide variation in the indoor relative humidity level. The relative humidity range, 32-37%, in a room complies with requirement by the U.S. Environmental Protection Agency [10, 11] of 30–50% whereby validating the results of this work.

The solar chimney works well even when the window is closed. The service age of 50years gives a reliability of 0.711 for the chimney-collector unit service life.

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