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Optimization and modeling of a solar air system for residential thermal comfort in tropical climate

Andry Thierry Randrianarinosy, Jean Marc Fabien Sitraka Randrianirina, Liva Graffin Rakotoarimanana, Falinirina Andrianjatovo, Zely Arivelo Randriamanantany

Institute for Energy Management IME, University of Antananarivo, University of Antananarivo BP 566, Antananarivo 101. Madagascar

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Abstract— *This study presents a solar air system designed for heating, cooling, and air conditioning in buildings. The system uses a flat-plate solar collector and a photovoltaic panel to capture solar energy. Heated air circulates through a thermal chamber to maintain indoor comfort. An electric resistor and a cold-water circuit provide backup heating or cooling. The thermal modeling is based on analytical equations and an energy signature method. Simulations are performed using Matlab with local data from Antananarivo. The system operates using a thermodynamic process similar to the Carnot cycle. Results show variable thermal efficiency throughout the day, with a performance coefficient above 3. This system ensures thermal comfort while reducing fossil energy consumption. It fits well with tropical climate conditions and the needs of low-income households.*

Keywords— ***Air collector, Building thermal comfort, Photovoltaic system, Solar heating, Thermal modeling***

I. INTRODUCTION

Since the 1950s [1], global energy consumption has increased significantly. It rose from 2 Gtep/year to about 10 Gtep/year by 2000. This rise follows the evolution of human societies. The global population is growing rapidly. Urbanization and economic development are expanding. These trends drive increasing energy demand, especially in developing countries. In 2009 [2], more than 80% of consumed energy came from fossil fuels. Oil, natural gas, coal, and uranium still dominate the global energy mix. These energy sources have major environmental impacts. They release large amounts of carbon dioxide. They also emit methane during extraction. These gases worsen the greenhouse effect and global warming. In response, renewable energy provides a sustainable alternative. It can meet demand while protecting the environment.

Renewable energies come from continuous natural phenomena and are inexhaustible in the long term. They produce little or no pollution and are environmentally friendly. Their use is growing rapidly due to climate concerns and the rising cost of fossil fuels. This study focuses on solar energy, a clean, abundant, and easily exploitable source. The objective is to assess solar potential for applications such as domestic heating, cooling, and air conditioning, [3].

This work addresses challenges related to the use of solar thermal energy, a free and abundant resource, in an active system. The goal is to maximize its efficiency using thermal balance principles and analytical sizing methods.

The study begins with an overview of astronomical foundations of solar radiation and the key characteristics of the solar resource that affect system performance. It continues with a description of core solar technologies and components of a solar air system. Modeling, simulations, and sizing calculations are performed to assess the performance of the experimental setup. The analysis uses a global thermal balance approach and rigorous mathematical methods. Practical applications are then conducted in real conditions to test system efficiency over a defined period, and the results are processed and interpreted using Matlab software.

II. MODELING AND THERMAL ANALYSIS OF SOLAR ENERGY SYSTEMS

1. Solar parameters for energy system optimization

The Sun is the primary energy source for Earth. It is located approximately 150 million kilometers away and emits radiation similar to a black body at 5800 K. This electromagnetic radiation reaches the Earth in about 8 minutes, with 98% of its energy concentrated between 0.25 and 3 µm. Solar radiation enables life, influences the climate, and drives weather phenomena, [4].

Earth orbits the Sun in a slightly eccentric elliptical path. Its average orbital speed is about 30 km/s, [5]. The tilt of Earth's rotation axis causes seasonal changes. This tilt is responsible for the annual variation of solar declination. The Sun's position in the sky depends on several astronomical parameters: latitude, longitude, declination, hour angle, solar altitude, azimuth, and zenith distance.

These parameters determine the Sun's apparent trajectory and are crucial for optimizing solar collector orientation. The declination varies between ±23.27° depending on the season. The hour angle defines the Sun's position relative to solar noon. Solar altitude measures the Sun's elevation above the horizon. Azimuth indicates its horizontal direction. Zenith distance is the complement of the altitude angle.

2. Solar time and local energy applications

True Solar Time (TST) depends on Earth's rotation on its axis. It is defined by the solar hour angle at a given moment. The sun reaches its zenith at solar noon. TST varies due to the Equation of Time (ET), whose correction ranges from -14.3 to +16.4 minutes throughout the year. This variation is nearly sinusoidal and can be approximated by a formula.

Mean Solar Time (MST) simplifies TST by assuming a uniform Earth rotation. Universal Time (UT), also known as Greenwich Mean Time (GMT), is the MST at the Greenwich meridian. Legal Time (LT) is the official time used in each country. It is based on the time zone and local longitude.

For a given location like Antananarivo (L = 47°53′ E, time zone N′ = +3), a relation links TST, UT, and LT. This study helps to understand the local solar time structure, which is crucial for energy applications and climate modeling.

$$TST = LT + \frac{L}{15} - N' + \frac{ET}{60} \quad (1)$$

where TST is the True Solar Time, LT is the Legal Time, ET is the Equation of Time correction, L is the longitude of the location (e.g., 47°53′ E for Antananarivo), and N′ is the time zone number (e.g., +3 for Antananarivo).

3. Earth's Atmosphere and Solar Radiation Budget

The Earth's atmosphere is structured in superimposed layers: troposphere, stratosphere, mesosphere, and thermosphere. Each layer has specific thermal and chemical properties. The troposphere hosts most weather phenomena. The stratosphere contains the ozone layer, which absorbs ultraviolet radiation. The mesosphere and thermosphere complete the atmospheric structure, with temperature varying with altitude.

Dry air consists mainly of nitrogen (78%), oxygen (21%), and trace gases. Water vapor, carbon dioxide, and aerosols both natural and anthropogenic significantly affect solar radiation absorption. These components filter radiation across selective spectral bands.

The solar radiation received at the Earth's surface includes three components: direct radiation (unscattered), diffuse radiation (scattered by the atmosphere), and reflected radiation (albedo), which depends on surface characteristics. The sum of these components is defined as global radiation.

Irradiation measures the energy received over a period, commonly expressed in Wh/m². The clearness index, defined as the ratio of global to extraterrestrial radiation, classifies sky conditions (clear, partly cloudy, overcast). This index is essential for solar energy assessments and climatic analysis, [6].

$$G = G_d + G_r + G_{dif} \quad (2)$$

Where G_d denotes the direct solar radiation, G_r the reflected radiation, and G_{dif} the diffuse radiation.

4. Energy Flux and Angular Distribution of Radiation

Energy flux represents the amount of energy carried by a light beam per unit of time. It is expressed in watts and depends on the orientation and distance between the source and the receiving surface. A point source emits radiation toward a surface within a solid angle $d\Omega$, [7].

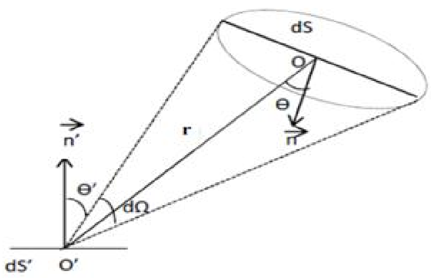

Fig.1 : Illustration of the energy flow

Where $\vec{n}$ and $\vec{n'}$ are the normal vectors to the surface elements dS and dS', respectively;

$r = O'O$ is the distance between the radiation source and the point on dS',θ is the angle between $\vec{n}$ and the emitted radiation; θ' is the angle between $\vec{n'}$ and the incoming radiation; and $d\Omega$ is the solid angle under which dS', is viewed from point O'.

The energy flux density is proportional to the source's luminance in the given direction. By integrating the luminance over the entire solid angle, the total energy flux received by the surface is obtained.

$$d\phi = \iint_s L' \frac{dS\, dS' \cos\theta \cos\theta'}{r^2} \quad (3)$$

Table 1 : Comparison of Solar Technologies and Role of Local Solar Time

Conversion Principle	Use of thermal collectors and heat transfer fluids	Use of semiconductor cells (P-N junction) to convert photons
Type of Process	Thermodynamic process	Chemical/electronic process
Main Compo-nents	Glazed collectors, metallic absorbers, heat pipes, fluid (water, glycol, air)	Photovoltaic cells (silicon), anti-reflective coating, electrodes
Output Type	Thermal energy for domestic hot water, space heating, drying, or cooling	Direct current (DC) electricity
Energy Storage	Stored as heat in fluids or thermal masses	Stored in batteries
Applicat-ions	Home heating, water heating, greenhouses, swimming pools, solar cooling	Power supply for electronic devices, lighting, buildings, solar farms
Efficiency Influences	Strongly influenced by sunlight availability, insulation, night conditions	Influenced by light intensity, cell temperature, and aging
System Type	Passive or active systems (with fluid circulation)	Standalone systems or grid-connected with battery storage
Advanta-ges	High efficiency for thermal energy production	Direct electricity generation, scalable
Disadvan-tages	Difficult energy storage and regulation,	Lower conversion efficiency, thermal losses at high

	performance drop in low sunlight conditions	temperatures

- ***Solar thermal collector***

The solar thermal collector converts solar radiation into heat using a heat transfer fluid. The addition of baffles improves thermal transfer in the air channel of the collector. The metallic absorber captures solar energy and transfers it to the fluid by conduction. The glazing limits thermal losses via greenhouse effect and optimizes solar absorption. The thermal insulation reduces heat loss on the lower and lateral sides of the collector. The copper coil increases thermal conductivity and air heat retention capacity.

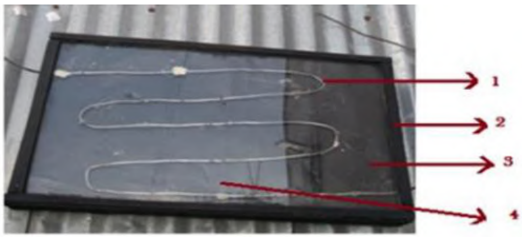

Fig.2 : Components of a flat-plate glazed collector.

The system (figure 2) consists of four main components: **1.**a metal coil for heat exchange, **2.** a black wooden frame providing structural support, **3.** a black sheet metal absorber surface to maximize solar energy capture, and **4.** a transparent cover that reduces heat loss while allowing solar radiation to pass through, [8].

- ***Heat transfer fluid***

The heat transfer fluid carries thermal energy in liquid or gaseous form. Air is used as the heat carrier despite its low thermal conductivity. A metal coil extends the air path and enhances thermal contact with the absorber. The heated air is reinjected into the box to optimize heat exchange. A built-in fan supports forced convection without overheating risk. Cold water is used as a second fluid to provide system cooling.

- ***Thermal Resistance***

The thermal resistance takes over when the outside temperature falls below the comfort reference. It provides fast and accurate heating through an automatically controlled regulation system. Powered by the battery, it complements the solar collector during periods of low sunlight. It regulates the return circuit temperature to prevent overheating in the air chamber. Its efficiency depends on the type of heat transfer: conduction, convection, or radiation. Its integration into the airflow circuits of the energy box enhances thermal stability and system performance.

$$R_C = \frac{\text{Difference between the interior temperatures of the casing and the room}}{\text{Heat flux}} \quad (3)$$

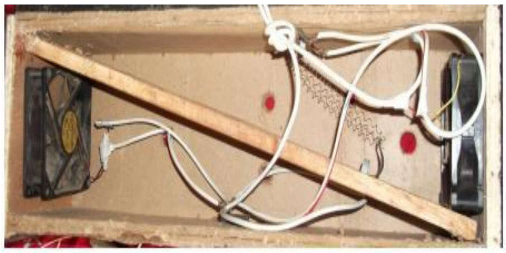

Fig.3: Photo of the air circuits inside the energy casing [24].

5. Ventilation

Ventilation ensures thermal comfort and air quality in a bioclimatic house. It affects temperature, air velocity, and humidity to improve indoor well-being. Natural ventilation uses air density differences to passively supply fresh air. Mechanical ventilation uses fans to actively control airflow and include heating or cooling. The fan coil unit enables heat exchange between air and the heat-transfer fluid inside the air chamber. Warm air is blown into the room at suitable pressure and speed depending on the season to maintain comfort.

6. Modeling and analysis of the systems used

The thermal modeling is based on simplifying assumptions to ease system analysis. A quasi-steady-state regime is assumed, with materials having constant properties. Temperatures within the collector and room are treated as uniform, and secondary thermal losses are neglected. The experiment was conducted over 30 days between July and August in Antananarivo. Ambient air temperature, affected by various climatic factors, plays a key role in thermal comfort. It is modeled using an approximate equation based on solar time and local weather data.

$$T_e(J,t) = \frac{T_{Max}(J)+T_{Min}(J)}{2} + [\frac{T_{Max}(J)-T_{Min}(J)}{2}]\sin(15t-120) \quad (4)$$

Where t is the true solar time (with $t = 12$ at noon, t = 0 or 24 at midnight,

$t = 13\ at\ 1\ PM$,

$t = 19\ at\ 7\ PM, t = 23\ at\ 11\ PM$,

$t = 11\ at\ 11\ AM$, etc.), and the monthly daily averages of minimum temperature $T_{Min}(J)$ and maximum temperature $T_{Max}(J)$ over 24 hours were recorded during local measurements in Antananarivo from July to August 2022, [9].

7. Thermal balance of the system

The thermal balance of the solar collector is established from the solar flux absorbed by the absorber, the useful heat flux transferred to the heat transfer fluid, the heat losses through insulation governed by Newton's law, and the stored energy within the collector depending on the air mass, its specific heat capacity, and the absorber's temperature variation, while the global, internal, and optical efficiencies of the collector vary based on internal parameters such as orientation and external factors such as solar irradiance, and the thermal inertia is experimentally determined by the temperature difference between the fluid's inlet and outlet, whereas the absorber's thermal diffusivity related to its thermal conductivity, density, and specific heat promotes heat transfer by conduction toward the heat transfer fluid within the collector, in interaction with the glass cover and air chamber.

III. ANALYTICAL METHOD

The analytical method helps properly size the solar installation to meet winter thermal needs. The system uses air-based collectors operating at low temperature with high airflow. A heat-transfer fluid, typically air, carries the collected heat to the living space. The system includes a heat exchanger or storage unit to ensure continuous energy supply. The study calculates the hot air and heating needs to maintain indoor comfort. Electric heaters and fans are added to overcome solar system limitations, especially at night.

1. Energy signature method

The method is applied under steady-state conditions where the building reaches thermal equilibrium with its surroundings. It models the heating load based on external factors such as solar radiation and outdoor temperature. The simplified thermal balance is expressed as a linear relation between heat load and climate conditions. Only heating or cooling periods are considered in the calculation. Assuming stable indoor temperature allows further simplification of the equation. The coefficients are estimated through linear regression using collected daily, weekly, or monthly data, [10].

$$Q' = x_r + y_r T_{ext} \quad (5)$$

The coefficients x_r and y_r_are estimated using linear regression based on scatter plots of daily, weekly, or monthly data collected at the household level, where Q' represents the heating load and T_{ext} the average outdoor temperature (°C).

2. Model to study the variation of outdoor temperature and solar irradiance

The model considers variations in solar radiation and outdoor temperature to evaluate the heating load. The linear regression equation links heating flux to solar input using least squares-calculated coefficients. Energy signature methods analyze the building's thermal behavior based on daily, weekly, or monthly data. They exclude transient states to better detect unusual energy consumption. Thermal models use outdoor temperature and solar energy both direct and diffuse as key parameters. Heat exchange occurs by convection at surface contact and by radiation depending on absorbed solar energy, [11].

$$(\rho C)_i V_i \frac{dT_i}{dt} = \sum_k \Phi_{ik}(t) + P_i(t) \quad (6)$$

where $(\rho C)_i$ is the heat capacity of the material composing the volume V_i is an elementary volume of the building, $P_i(t)$ represents the set of external energy inputs; and $\Phi_{ik}(t)$ denotes the heat fluxes exchanged at the interfaces of V_i .

3. Method for calculating the power of the collector

The thermal power of the collector is calculated based on air flow rate, air heat capacity, and the temperature difference between inlet and outlet. The volumetric heat capacity of air is estimated at 1.2 J/K/L under standard conditions. An initial method using volumetric flow showed limitations due to multiple unverified assumptions. An alternative and more accurate approach uses the mass flow rate and an average specific heat capacity of 1017.5 J/kg°C. This method allows for temperature-independent calculations if the collector is airtight. Energy consumption for heating, cooling, and air conditioning must comply with the thermal energy standards and remain within prescribed limits, [12].

$$P = 1.683E_{ng} - 17.11\Delta\theta \tag{7}$$

where E_{ng} represents the solar irradiance in W/m², and $\Delta\theta$ denotes the difference between the average inlet-outlet temperature of the system and the ambient temperature.

4. ***Method for calculating the overall power of the system***

The global power of the system is defined according to the NFP50-501 standard from September 1977. It depends on the received solar irradiance and the thermal difference between the system and outdoor air. The average system temperature is calculated from the inlet and outlet temperatures. This average temperature is then compared to ambient temperature to assess performance. The full expression for global power includes surface area and solar radiation intensity. This method allows for evaluating the overall energy efficiency of the solar installation, [13].

$$P = Q_m C_p (T_{cs} - T_{fe}) \tag{8}$$

Where Q_m is the mass flow rate in liters or kg/s (with $Q_m = 0.02$ kg/s used in this study), and C_p is the specific heat capacity of air at constant pressure (in J/kg·°C).

5. ***System operation: heating and cooling***

The system operates by capturing solar energy using a flat air solar collector and a photovoltaic panel. The heat transfer fluid circulates through a coil to deliver the collected heat. A valve-based control system directs the fluid flow toward the energy chamber. In winter, if the air temperature is too low, an electric resistor powered by the photovoltaic panel provides heating. In summer, when the temperature exceeds the comfort level, the fluid is routed to a cooling system using chilled water and ventilation. This operation ensures thermal regulation of the dwelling, following a thermodynamic process similar to the Carnot cycle, [15].

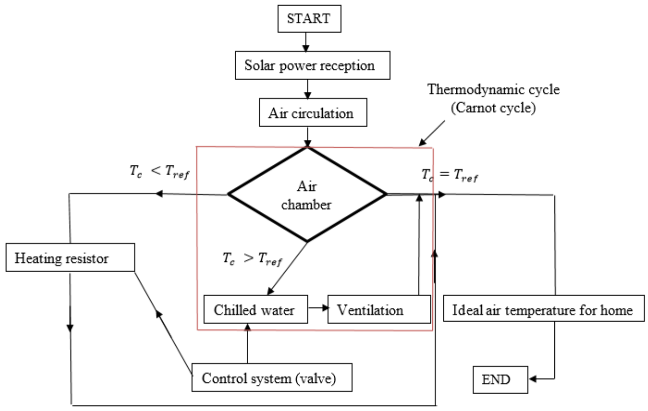

Fig.4 : Block diagram of the system operation

IV. RESULT AND DISCUSSION

1. ***Results on the overall efficiency of the collector***

The coupling of thermal modeling with dynamic simulation integrates key parameters such as air temperature, heating, cooling, or ventilation intensity, enabling efficient analysis of the system's behavior under the specific climatic conditions of Analamanga; the results from the global thermal balance calculation, using a formula implemented in Matlab, show that the flat air solar collector exhibits variable thermal efficiencies throughout the day, with optimal performance when the temperature difference between the collector and the ambient air is minimal, while the collector's inclination and the incidence angle of solar radiation directly influence transmission through the glazing, thus explaining the curve overlap caused by thermal flux variations during sunlight exposure.

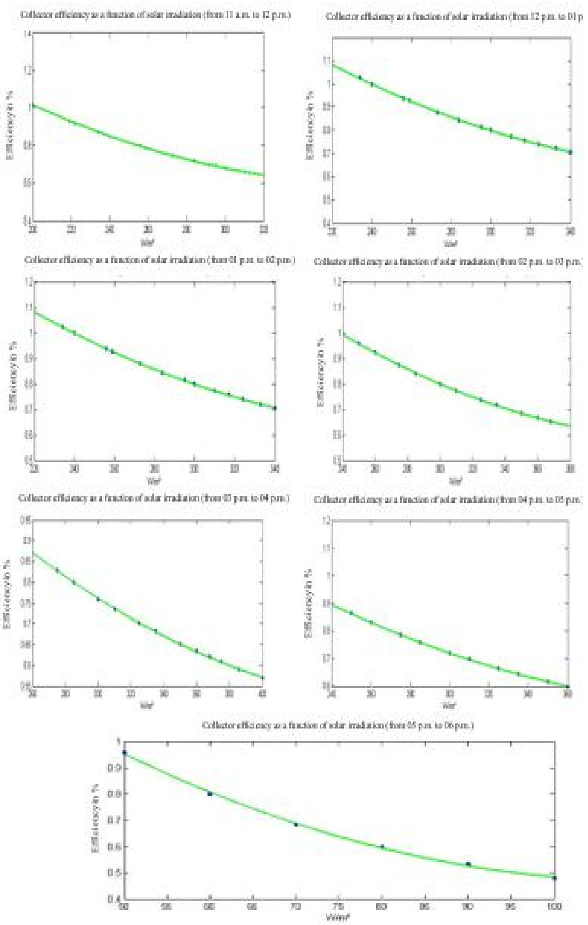

Fig.5 : Overall efficiency received by the collector

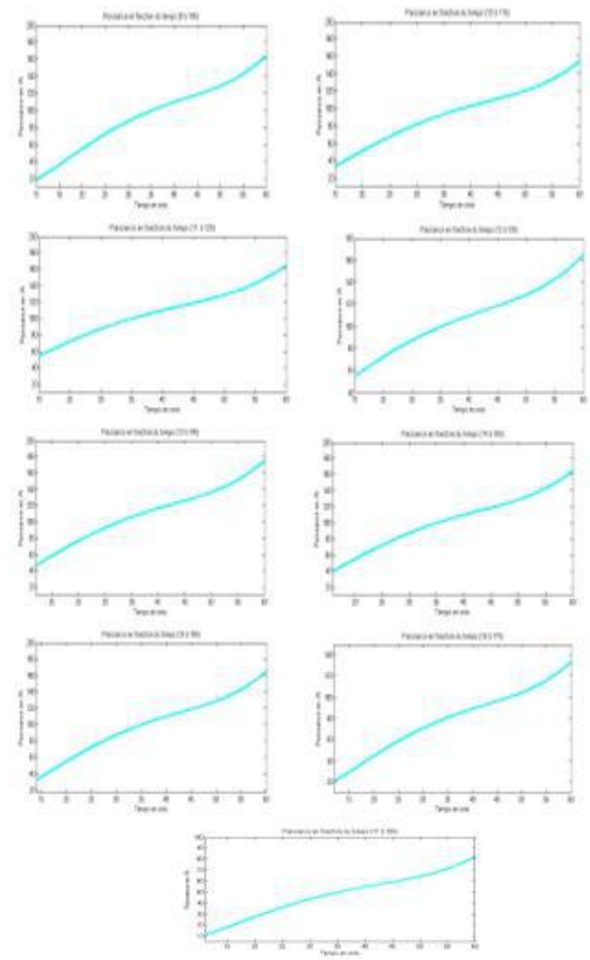

Fig.6 : Total power received by the collector

2. ***Total and instantaneous power received by the collector***

The fig.6 presented illustrate the variation of global and instantaneous power received by the flat plate air solar collector throughout the day. The collected thermal power reflects the contribution of solar energy to heating demands. The calculations show that the power varies depending on sunlight exposure and time of day. The curves allow evaluation of the solar coverage in relation to total energy consumption. An energy control box, combined with a switch and a battery, ensures daily thermal management. The system can simultaneously provide heating and cooling depending on requirements. Continuous observation of the system ensures a better understanding of its operation. The capture methods, measurement series, and calculation tools enable a rigorous evaluation. This setup can also serve as a reference for comparative studies with other similar systems.

3. ***Temperatures obtained in the floor***

The temperature on the floor is obtained from the calculation of the overall thermal balance of the air-heated floor used in this system. The application of this formula through the energy signature method and the Matlab software shows the temperature trend over one hour. This temperature variation is illustrated in the figure below.

The floor temperature (fig.7) gradually increases over time, starting with a slow rise during the first 40 minutes. This period indicates a significant thermal inertia of the system. After the 40th minute, the temperature rises more rapidly, reflecting a stronger activation of the heating mechanism. This shows the system's increasing thermal efficiency as time progresses.

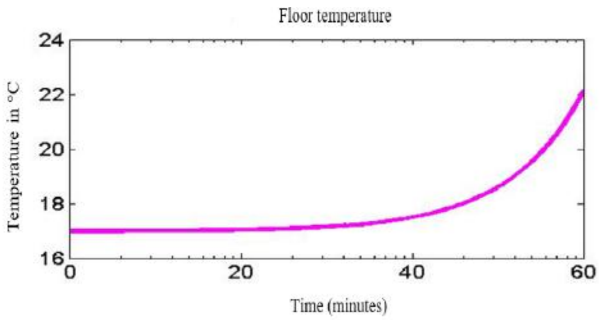

Fig.7 : Temperature obtained on the floor within one hour.

Due to the continuous increase in temperature received over one hour during the day, the indoor temperature becomes very high, exceeding the comfort temperature. However, the application of the cooling method in this system (which involves passing the heat transfer fluid through chilled water and using ventilation) stabilizes and maintains the comfort temperature in the room. Therefore, the temperature received on the floor throughout the day is shown in the curve below.

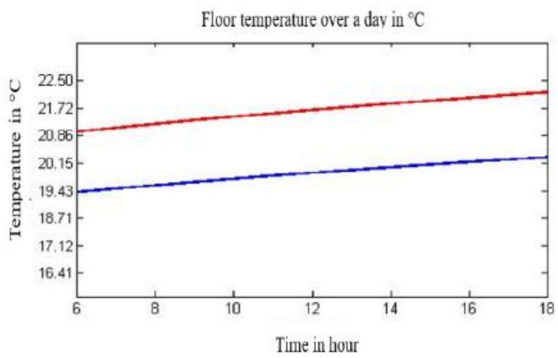

Fig.8 : Floor temperature recorded throughout the day

The floor temperature (fig.8) increases slightly from 6 a.m. to 6 p.m., reflecting a moderate variation under external conditions. The two curves likely compare two thermal scenarios or different floor layers. The red curve remains consistently higher than the blue one, suggesting better thermal performance or an additional energy input. The relatively stable slopes indicate a maintained thermal balance over time.

4. *Performance coefficients*

The studied system consumes little electricity and operates with various installation levels. It achieves a coefficient of performance greater than 1, proving its efficiency. The COP represents the ratio between recovered energy and energy delivered indoors. A COP of 3 means that for each 1 kWh consumed, 3 kWh of heating are produced. The COP decreases when the outside temperature is lower. Our system reached a COP of 3.38 with 160 Wh recovered and 47.2 Wh delivered, confirming its high performance.

V. CONCLUSION

The solar system studied uses air as the heat transfer fluid to heat or cool indoor spaces. It captures solar energy through an air collector and a photovoltaic panel. It provides constant thermal comfort throughout the seasons. Thus, it heats during winter and cools during summer. Then, it uses thermal storage and ventilation to regulate indoor temperature. The system shows good energy efficiency in the tropical climate of Antananarivo. It reduces fossil energy dependence and lowers household costs. Finally, it offers a sustainable, simple, and suitable solution for low-income areas.

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