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Performance Analysis of a Solar Air Heating System for Thermal Comfort in Tropical Buildings: Case Study in Madagascar

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Abstract— *This paper investigates the performance of a solar air collector integrated into a hybrid heating and cooling system for buildings in tropical climates, specifically in Madagascar. The study analyzes internal and external heat gains, calculates the thermal loads, and evaluates the efficiency of the solar system based on real temperature measurements. The results show that the solar collector can ensure thermal comfort, especially during morning and evening periods, and can also be used for domestic hot water production. With a coefficient of performance (COP) of 2 and a total installation cost significantly lower than conventional systems, the proposed solution proves to be energy-efficient, cost-effective, and suitable for local implementation. The system offers a sustainable alternative to conventional air conditioning by using locally available materials and renewable energy.*

Keywords—Air conditioning, Energy efficiency, Renewable energy, Solar collector, Thermal comfort

I. INTRODUCTION

Air conditioning refers to a technique used to control the indoor climate of a closed space. Thus, temperature, humidity, and air quality are regulated to ensure thermal comfort. Since ancient times, civilizations have sought natural methods to reduce indoor heat. Egyptians and Greeks used water evaporation through porous jars to cool the air. In the 19th century, the first vapor-compression refrigeration machines marked the rise of modern cooling, [1], [2]. In 1834, Jacob Perkins built a mechanical compression machine using ether as a refrigerant, [3]. In 1842, John Gorrie developed a device for making ice, considered a precursor to air conditioning, [4]. Then, in 1859, Ferdinand Carré introduced an absorption system using water and ammonia, [5]. The 20th century brought widespread integration of air conditioning in vehicles, starting in the U.S. in 1955. Today, air conditioning is a standard technology offering discretion, energy efficiency, and health-enhancing comfort, [6].

This work aims to evaluate how air conditioning systems can provide comfort while reducing energy consumption. It analyzes internal and external heat gains to optimize cooling and heating efficiency. Then, it proposes the integration of solar collectors to improve energy performance and reduce operating costs. Finally, the goal is to demonstrate a sustainable solution adapted to tropical climates like Madagascar.

To reach this objective, the study begins by explaining the principles and functioning of air conditioning. Then, it presents the criteria for thermal comfort and the calculation of heating and cooling loads. Next, it examines different types of air conditioning systems and their energy consumption. Finally, it proposes a hybrid solution combining conventional air conditioning with solar thermal collectors and evaluates its efficiency and cost-effectiveness.

II. AIR CONDITIONING

In residential buildings, air conditioning ensures thermal comfort by lowering indoor temperatures by 5 to 8 °C compared to outdoors during hot periods, and by providing heating during cold periods, [7]. Thus, it also dehumidifies the air to maintain optimal indoor comfort. However, air refrigeration is energy-intensive because it offsets thermal gains from solar radiation, air renewal, and internal activities. Sensible heat results from the temperature gap between inside and outside, while latent heat is linked to air dehumidification. Moreover, occupants and lighting contribute to both sensible and latent internal gains. Finally, reducing cooling energy consumption requires solar protection, airtightness, and precise control of air conditioning settings to maintain a constant indoor atmosphere.

2.1. Thermal Comfort Optimization through Air Conditioning Performance Analysis

An air conditioner operates on the same principle as a refrigerator: it removes heat from a room and releases it outside using a compressor filled with refrigerant, [8]. Thus, energy consumption depends directly on the set temperature and operating hours, especially when the room is poorly insulated. Then, the lower the desired indoor temperature, the higher the energy use, following an almost linear relationship particularly in sun-exposed spaces. To properly assess air conditioning performance, key physical parameters must be considered: temperature, heat, power, pressure, and humidity. These values, expressed in standard units (°C, W, J, Pa, %), help quantify thermal comfort objectively. Finally, air humidity plays a critical role in comfort perception and must be managed alongside temperature control.

2.2. Determinants of Thermal Comfort and Seasonal Adaptation Strategies

Thermal comfort refers to the state of physical well-being experienced by the human body in response to the thermal environment, regardless of outdoor conditions, [9]. Thus, it is influenced by factors such as metabolism, clothing, air and surface temperatures, relative humidity, and air velocity. In thermal stress situations, the body reacts through behavioral adjustments or physiological responses. Then, heat is exchanged between the body and the surroundings via conduction, convection, radiation, and evaporation. In winter, ensuring comfort involves proper insulation, suitable glazing, controlled heating, and maintaining relative humidity between 40% and 60%. Finally, in summer, comfort is achieved by reducing solar and internal heat gains, enhancing natural ventilation, and keeping indoor temperatures between 18 °C and 25 °C with air speed under 0.2 m/s.

$$T_{operative} = \frac{T_{wall} + T_{air}}{2} \quad (1)$$

2.3. Cooling and Heating Capacity Analysis for Optimal Air Conditioning Performance

The cooling power helps to cool the air in a specific space. It prevents thermal shocks to ensure comfort. This power must be calculated through a detailed heat load analysis. The thermal balance includes all internal and external heat sources. The temperature difference between indoors and outdoors should not exceed 8°C. An undersized unit cools insufficiently. An oversized unit consumes too much and causes discomfort, [10].

The heating power of an air conditioner applies to units that can produce both cold and heat, using either electric resistance or reversible operation. Thus, electric resistance heating spreads heat via ventilation, while reversible systems work like heat pumps, with a high COP and the ability to extract heat from the outside. Then, dehumidification occurs during cooling mode and is measured in liters per day, directly improving indoor comfort. The power consumption, expressed in watts, varies between average and peak values, and plays a key role in long-term energy cost. Air conditioning systems must be sized based on thermal load calculations, which include internal gains (from people, lighting, and appliances) and external gains (solar radiation, conduction, and infiltration). Finally, the total thermal load is the sum of both sensible (QS) and latent (QL) loads, as defined in equation (2).

$$Q_T = Q_L + Q_S \qquad (2)$$

2.4. Classification and Functional Diversity of Air Conditioning Systems

There are different types of air conditioners designed to meet specific thermal needs of buildings. Thus, the direct expansion air conditioner cools the air directly using a refrigeration circuit filled with refrigerant. Next, monobloc systems such as mobile units or "Windows" types are built for individual use and have limited cooling capacity. Moreover, some systems use water to cool the condenser, like exposed water consoles, but they produce noise. In addition, mono-split and multi-split units, with indoor and outdoor components, provide adjustable thermal comfort for one or several rooms. Furthermore, ducted air conditioners installed in ceilings offer a discreet centralized air diffusion solution. More advanced systems such as VRV or multi-flex can cool large buildings efficiently. Finally, all these systems can be classified as individual or centralized depending on distribution mode, airflow rate, and fluid type used.

2.5. Building Thermal Science for Energy Efficiency and Comfort

Building thermal science helps to understand heat transfer in order to better design or renovate structures. Thus, it aims to reduce energy losses while ensuring thermal comfort for occupants. Next, it considers material properties such as thermal conductivity and thermal resistance. Moreover, understanding energy flows is essential to properly size technical systems. In addition, wall performance depends on its ability to resist conduction, convection, and radiation. Furthermore, glazing plays a key role through its emissivity, solar factor, and Ug coefficient. Likewise, thermal bridges, whether integrated or at junctions, must be minimized to avoid energy loss. Finally, proper thermal management reduces annual energy consumption and improves indoor comfort.

III. METHOD FOR CALCULATING THE THERMAL LOAD OF AIR CONDITIONING IN A TROPICAL CLIMATE

The calculation of thermal load in tropical climates relies on a thorough analysis of all factors affecting heat gain. Thus, the building's orientation in relation to the sun and surrounding obstacles determines solar inputs. Then, the geometry of the room (dimensions, ceiling height) affects the air volume to be cooled. The type and thickness of construction materials directly impact thermal exchange. Moreover, the color of outer surfaces influences heat absorption or reflection. External conditions and interactions with adjacent spaces also modify cooling needs. Internal heat sources such as occupants and appliances must also be considered. Finally, this method aims to optimize air conditioning systems and avoid oversizing that leads to excessive energy consumption, [11].

To determine the peak cooling load time of an air conditioner, a two-step method must be followed. First, the rooms must be properly oriented among 31 possible options; in Madagascar, located in the Southern Hemisphere, the most effective orientation is toward the Northeast. Then, the maximum refrigeration load time must be identified, which coincides with the peak solar gain. This critical hour varies depending on the building's orientation, as shown in the tropical zone table.

Table 1 : Maximum refrigeration load hours depending on room orientation in tropical climates.

Room Orientation	Number of Exposed Walls	Exposed Walls	Maximum Cooling Hours
1	1	N	14
2		NE	14
3		E	9
4		SE	10
5		S	13
6		SW	16
7		W	17
8		NW	17
9	2	N - E	9
10		NE - SE	9
11		S - E	10
12		SE - SW	15
13		S - W	16

14		SW - NW	16
15		W - N	17
16		NW - NE	17
17	3	W - N - E	16
18		NW - NE - SE	16
19		NE - E - S	10
20		SE - S - SW	15
21		E - S - W	16
22		SE - SW - NW	16
23		S - W - N	16
24		SW - NW - NE	16
25	4	S - W - N - E	15
26		SW - NW - NE - SE	16

3.1. Internal Heat Gains

3.1.1 Gains from Occupants in the Room

They are based on the indoor temperature and the activity level of the people, [12]. These loads are divided into two types: sensible heat and latent heat.

$$Q_{s\acute{e}cl} = \frac{C_{s\acute{e}cl} * n_{\acute{e}cl} * \Delta t}{24} \quad (3)$$

Where $Q_{s\acute{e}cl}$ represents the heat gain from lighting, calculated using the number of lamps ($n_{\acute{e}cl}$), their total operating duration (Δt), and the sensible heat per lamp ($C_{s\acute{e}cl}$), which depends on the lamp type

$$Q_{locc} = \frac{C_{locc} * n_{occ} * \Delta t}{24} \quad (4)$$

Where Q_{locc} represents the latent heat gain from occupants, determined using the latent heat per person (C_{locc}) provided in Table 1.

The sensible and latent heat gains from occupants depend on the indoor ambient temperature and the level of activity.

Table 2 : Heat emitted by people under optimal indoor temperature conditions.

Activity	Heat Emission by Activity and Ambient Temperature						Total Heat Emission [W]
	Sensible Heat [W]	Latent Heat [W]	Sensible Heat [W]	Latent Heat [W]	Sensible Heat [W]	Latent Heat [W]	
	25 °C		26 °C		27 °C		
Sitting at rest	65	37	62	40	60	42	102
Light work	67	49	63	59	56	60	118
Standing, slow walking	68	63	65	67	57	74	131
Eating	77	84	71	90	64	97	161
Easy work	80	140	72	148	67	153	220
Dancing	88	161	80	169	75	174	249
Heavy work	149	277	142	284	138	290	427

3.1.2 Gains from Lighting

Lighting contributes only to sensible heat gains, as it converts the electrical energy consumed into heat.

$$Q_{s\acute{e}cl} = \frac{C_{s\acute{e}cl} * n_{\acute{e}cl} * \Delta t}{24} \quad (5)$$

Where $Q_{s\acute{e}cl}$ represents the heat gain from lighting, based on the number of lamps ($n_{\acute{e}cl}$), their total operating time (Δt), and the sensible heat ($C_{s\acute{e}cl}$) depending on the lamp type.

3.1.3 Gains from Machines or Electrical Equipment

These gains are calculated using the following formula:

$$Q_{mach} = \frac{N_m * t_m * Pm}{24} \quad (6)$$

where Q_{mach} represents the heat gain from machines, calculated using the number of electrical machines (N_m), their operating time (t_m), and power rating (Pm).

3.1.4. Total Internal Heat Gains

The total internal heat gain is the sum of the gains from occupants, lighting, and machines:

$$Q_{int} = Q_{occ} + Q_{s\acute{e}cl} + Q_{mach} \quad (7)$$

3.2. Quantification of External Heat Gains and Thermal Load in HVAC Systems

The thermal load of air conditioning mainly depends on external heat gains. These gains come from heat transmission through walls, roofs, floors, and glazing. The amount of heat transmitted is calculated by the formula:

$$Q_{str} = U \times S \times \Delta\theta \quad (8)$$

where U is the thermal transmission coefficient, S is the surface area, and Δθ is the temperature difference.

Solar radiation also contributes to heat gain, especially on walls and windows. This radiation is partly absorbed depending on the color and nature of the surfaces. The heat absorbed by solar radiation on a wall is calculated with:

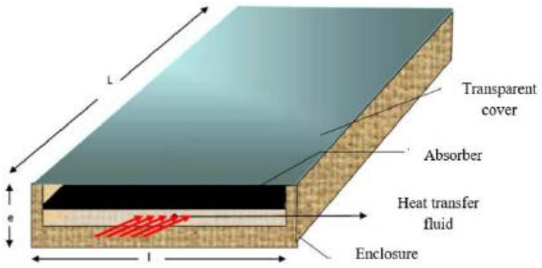
$$Q_{sRm} = \alpha * F * S * Rm \qquad (9)$$

where α is the absorption coefficient, F is the solar radiation factor, S is the surface area, and Rm is the solar radiation intensity.

Furthermore, air renewal and infiltration bring sensible and latent loads into the air-conditioned space. These loads increase the required power of the air conditioning system. The sum of sensible and latent loads forms the total thermal load to be compensated. Therefore, controlling these heat gains is essential for properly sizing an air conditioning system in a tropical climate.

3.3. Solar Air Collector Principles and Performance Factors

Solar thermal collectors capture solar radiation and convert it into usable heat energy. A solar collector transforms free and available solar energy into heat or electricity. It transfers this energy to a heat transfer fluid, such as air or water. Various types of solar collectors exist, including unglazed flat-plate, glazed flat-plate, vacuum tube, and concentrating collectors. Unglazed flat-plate collectors operate at low temperatures and are mainly used for pool heating or preheating water. Glazed flat-plate collectors are the most common and are used for domestic hot water production, with typical temperatures below 70°C. Vacuum tube collectors provide high efficiency at elevated temperatures and are used for industrial hot water or steam production. Concentrating collectors focus solar radiation using reflectors to generate electricity. Flat-plate air collectors use air as the heat transfer fluid and are suitable for space heating applications. For this project, a flat-plate air collector was selected to heat an indoor space efficiently and economically.



Figure

The working principle of a solar air collector is based on the greenhouse effect. Solar radiation passes through the transparent cover and heats the absorber, which then emits infrared radiation that is trapped inside the collector. This absorbed energy increases the temperature of the material and is transferred to the air by thermal contact. The performance of the collector depends on external parameters (solar radiation, ambient temperature, wind speed) and internal parameters (geometry, fluid flow rate, and material temperatures), [13].

3.4. Orientation and Tilt Optimization of Flat-Plate Solar Collectors

The flat-plate solar air collector must be installed in a fixed position with optimized orientation and tilt, depending on the location and the intended operating season, to maximize energy collection, [14]. In practice, and depending on the intended use of solar energy, the following rules are applied:

The collector must be placed in a location free from shading obstacles that may block solar radiation from reaching the surface.

Orientation and tilt depend on the geographical location, specifically the latitude and longitude of the site.

In Analamanga, the collector orientation is the same as that of bioclimatic buildings in Madagascar, facing North-East. The tilt angle is calculated based on the latitude, and it is given by the following formula:

$$\theta = \Psi \pm \delta \qquad (10)$$

Where θ is the tilt angle (°), Ψ is the site latitude, and δ is the solar declination (starting from 23° in our country)

3.5. Electric Heating Integration and Thermal Regulation in Solar Systems

The electric heating resistor heats indoor air during low solar radiation and at night. It is coupled with an electric fan, which prevents condensation in electrical components and ensures homogeneous air distribution. Thus, it provides both warm air and good air circulation to maintain thermal comfort. The regulation system controls the airflow needed in the building and supports the solar heating system. The underfloor heating distributes the collected solar heat through a copper serpentine tube using a heat-transfer fluid. Temperature is then measured at various points, including ambient air, solar collector, and heat-transfer fluid inlets and outlets, using a probe thermometer.

IV. RESULTS

4.1. Thermal Data Analysis and Power Calculation of Solar Air Collectors

The efficiency of the solar collector and the useful power of the air conditioner depend on the temperature measurements from the collector and the heating resistor temperature. Weather conditions during the test period influence the results. The experiments were conducted over a period of 7 days, with a time interval of 60 minutes. Tests were carried out from 6:00 a.m. to 5:00 p.m.

The following temperatures were measured:

- Glass temperature (Tv)
- Absorber temperature (Tab)
- Outlet fluid temperature (Tfs)
- Inlet fluid temperature (Tfe)

All recorded data during the test period are presented in Annex 1. The temperature of the heating resistor was maintained at 35°C. A sample of the results is shown in the following table 3:

Table 3 : Sample of the results during the day 10/11/22

Date	Hour	T_v °C	T_{fs} °C	T_{fe} °C	T_a °C	Humidity %
10/11/22	6h	28	30	19	18	50
	7h	29	30.8	20	18.5	45
	8h	30	31	21	19	42
	9h	32	34	22	21.5	42
	10h	36.8	38	24	22	42
	11h	39	41	25	21	42
	12h	41	43	25	21	42
	13h	40.8	42	24.5	20	42
	14h	39.5	41.8	24	20	42
	15h	38	41	23	19.5	42
	16h	37	40	22	18.5	42
	17h	33	39	22	18	43

According to these results, the power of the solar collector can be calculated, as it depends on the outlet and inlet temperatures of the heat transfer fluid. Based on Equation (48), the calculated power is 356.125 W. The data results are also presented in graph form using MATLAB software. Temperatures are expressed in degrees Celsius (°C).

The following results show the air solar collector temperatures, including:

Outlet temperature of the heat transfer fluid

Inlet temperature of the heat transfer fluid

Ambient temperature of the air-conditioned room

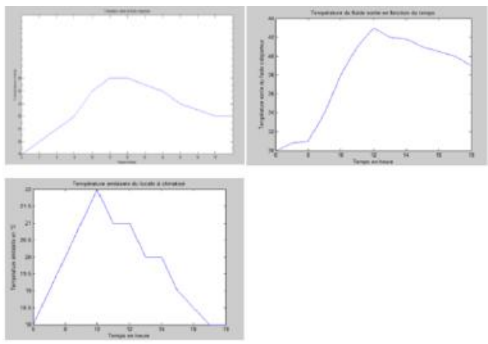


Figure:

All heat gains in the building are identified and classified as internal or external. Internal gains depend on the operation time of equipment and the presence of occupants. External gains depend on the thermal transmission coefficients of the building envelope. The total heat gains are equal to the power of the installed air conditioner. Solar collector temperatures and comfort temperatures vary with local weather conditions. Heating is needed in the morning and evening, and cooling is needed at midday. Heating is provided by the solar collector, and cooling is ensured by natural ventilation and air infiltration. The energy systems, including battery, solar panel, and controller, must be properly sized to meet daily thermal needs.

4.2. Coefficient of Performance and Power Assessment in Heating Systems

The coefficient of performance (COP) represents the efficiency of the heating system and has no unit. It is essential for heating system installation and plays a key role in the profitability of the device. COP is calculated as the ratio between the heat produced by the solar collector and the energy consumed to produce it. In this project, COP = 2, which indicates good efficiency and low energy consumption.

$$COP = \frac{Q(kWh)}{W(kWh)}$$

The power of the air conditioner can be determined to avoid under-sizing, excessive energy use, and unnecessary economic cost.

$$P_{annual} = \frac{(612.01\text{W}\times 12\text{h}\times 360)}{1000} = 2643.8\text{kWh/year}$$

V. DISCUSSIONS

According to the results, the inlet and outlet temperatures of the heat transfer fluid can be used to heat water. This means the solar collector is capable of producing domestic hot water. Madagascar has a warm climate during the summer, so the heating system is not required during this period, as natural heat is sufficient. The solar collector can therefore be used to heat water in summer and to produce space heating in winter. In this study, the collector was tested for water heating, and it can heat 20 liters per hour. A solar thermal tank is required to store the hot water. The most suitable and easy-to-install storage system is the thermosiphon solar tank. The domestic hot water demand depends on the user, so the collector size, coil diameter, and storage tank surface must be increased for higher water consumption.

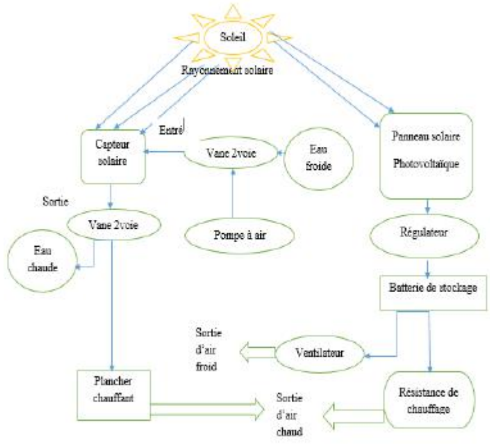


Figure:

Madagascar is located in a tropical zone, which is suitable for using a solar air heating system for buildings. This system is cost-effective and economical, as all construction materials are locally available and easy to install. According to Table 11, the total cost of the solar and heating installation is 499,000 Ar.

In comparison, conventional air conditioners in Madagascar cost between 1,500,000 Ar and 3,000,000 Ar and require monthly electricity payments, making the proposed system more economical and profitable.

VI. CONCLUSION

This study demonstrates that solar air collectors can effectively meet heating needs in tropical climates like Madagascar. The experimental results confirm that the system provides sufficient thermal power to ensure indoor comfort during cooler periods. The collector operates efficiently with a COP of 2, indicating good energy performance. Furthermore, it allows dual use for both space heating and domestic hot water production.

The system proves to be simple to install, low in maintenance, and cost-effective compared to conventional air conditioning units. All materials used are locally available, which facilitates replication and scalability. The integration of solar energy into building thermal regulation reduces energy bills and environmental impact.

In conclusion, the hybrid solution combining solar air heating with basic ventilation offers a sustainable and affordable alternative adapted to tropical conditions. This approach contributes to energy transition goals while improving living conditions in warm regions.

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