International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 3, June, 2023, pp. 749-754
Journal homepage: http://iieta.org/journals/ijht

Influence of Natural Convection Ventilation of the Space Between the Roof and the False Ceiling on the Distribution of the Temperature in a Room

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https://doi.org/10.18280/ijht.410331

Received: 28 February 2023
Accepted: 16 June 2023

Keywords:
natural convection, thermal inertia, thermal comfort, roof ventilation

ABSTRACT

Buildings are responsible for a significant portion of global energy consumption and greenhouse gas emissions, so improving their energy efficiency can significantly mitigate their environmental impact. Designing buildings to take advantage of natural ventilation can be one way of improving energy efficiency and reducing energy consumption. The purpose of this experimental work is to compare the thermal behavior of pitched and flat roofs, as well as the effect of natural convection ventilating of both types of roofs on the evolution of temperature in a room with dimensions of (750×750×870 mm^3), chipboard sidewalls and floor, and reinforced concrete ceiling (slab). A plasterboard, playing the role of a false ceiling, divides the room into a "living" space and a ventilated space delimited by the upper ceiling. The upper face of the slab is subjected to a constant heat flow. The ventilated space is ventilated by natural convection through windows placed in two opposite walls. Temperature measurements are provided by thermocouples. The results show that natural convection ventilation of the space between the roof and the false ceiling has a positive effect for both types of roofs, but it is better for the pitched roof.

1. INTRODUCTION

In regions characterized by hot and dry climates with high solar irradiance levels, such as Algeria, achieving indoor thermal comfort can pose a significant challenge. Traditional buildings in these areas have utilized multiple strategies to enhance thermal comfort including the use of clay and stones, which can have natural insulation properties, and the implementation of roof overhangs, high ceilings, light-colored roofing materials, and wind towers.

However, as buildings increasingly adopt European design aesthetics and building materials that are less compatible with the hot and dry climate of northern Africa, maintaining thermal comfort has become more difficult. As shown in Figure 1, less efficient buildings do not provide adequate thermal comfort to their occupants without the resort to the use of air conditioning appliances. This not only leads to direct and indirect greenhouse effects, but also exacerbates power cuts during periods of intense heat.

As a result, the importance of improving the efficiency of buildings through various methods, such as material choice, roof design, and natural and mechanical ventilation, has become increasingly evident in the pursuit of sustainable building design. Therefore, it is essential to conduct thorough studies to identify the most effective approaches that can be implemented to achieve this goal. Given that roofs contribute to around 50-60% [1] of a building's heat gain, it is imperative to explore and adopt different techniques to minimize the roof's impact on heat gain in buildings. Roof ventilation, in particular, plays a vital role in reducing summer thermal loads caused by solar radiation, especially in buildings with a moderate height and a large area (e.g., small houses, industrial buildings) [2]. This is particularly important in areas such as Algeria where there are high atmospheric temperature differences between day and night.

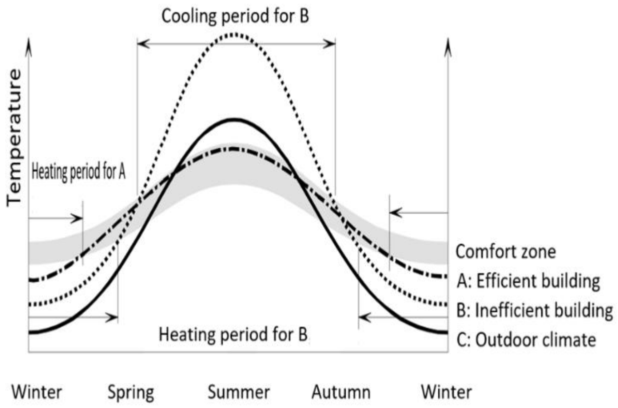

Figure 1. Evolution of temperatures in buildings throughout the year, without the effect of heating or cooling systems [3]

Roof natural ventilation relies on a variety of mechanisms, including wind-induced ventilation, stack ventilation, and solar-induced ventilation. Wind-induced ventilation [4] involves utilizing the flow of air over the roof to create a pressure differential, thereby driving air movement through the building. Stack ventilation, on the other hand, relies on the stack or chimney effect to drive air movement [5]. Warm air rises and escapes through openings at the upper levels, while cooler air is drawn into the building through openings at the lower levels, creating a natural flow of air through the building.

Solar-induced ventilation harnesses solar energy to drive air movement through the building using solar chimneys with glazing surfaces enhancing the upward air movement or stack effect significantly [6].

Numerous studies have been conducted to examine the thermal behavior of ventilated building facades and roofs, and to quantify the energy efficiency improvement that can be achieved through the ventilation of building walls and roofs.

Ciampi et al. [7] have studied the energy saving achievable by using ventilated facades in which the airflow inside the air duct due to stack effect. The energy saving increases remarkably as solar radiation intensity increases; the bigger the solar radiation is, the more efficient ventilated facades turnout to be from an energy saving point of view.

Sojoudi et al. [8] have investigated the natural convection heat transfer in an attic-shaped enclosure, which is filled with air and has two inclined walls that are differentially heated. The governing equations were solved using the finite volume-based software ANSYS 15 (Fluent). The study analyzes the dependency of various fluid flow and heat transfer parameters, including the Rayleigh number, heater size, heater position, and aspect ratio. The numerically obtained results are compared with those in the literature.

Miller et al. [9] created an algorithm for predicting the rates of air flow and heat transfer in an inclined air space that is heated from either the top or bottom. The algorithm was incorporated into a program for simulating attics and tested using data from real-world experiments on roofs with stone-coated metal shingles and ventilation above the insulation.

Olenets and Piotrowski [10] presented and validated a model for predicting airflow and heat transfer in a horizontal, naturally ventilated space. The space is modeled as a rectangular channel with cooled and heated surfaces on the top and bottom. The results of the model were compared to a field experiment and were found to be consistent with an error rate of less than 9%.

Rawat and Singh [1] carried out a comparative literature review of cool roof thermal performance in various regions. They concluded that an overall cool roof is a sustainable, energy-efficient, eco-friendly, and financially viable technology for reducing energy consumption and maintaining thermal comfort in buildings.

Omar et al. [11] studied the energy saving potential with a Double-Skin Roof ventilated by natural convection in Djibouti. Their results showed that use of the ventilated roof considerably reduces heat flux coming into the building (almost 50% of energy saving rate), and that adding insulation in the inner slab to the ventilation increases the energy saving up to 85%.

Ibrahim et al. [12] have performed roof optimization on a small-scale model and verified the results by simulation using computational fluid dynamic (CFD) software, namely ANSYS 18.0. From the data obtained, it was found that the opening in the roof reduced the indoor temperature.

Ciampi et al. [2] have performed an energy analysis of ventilated and micro-ventilated roofs. They showed that an energy saving, even exceeding the 30%, could be achieved by using ventilated roofs in summer, compared to the same non-ventilated structure.

Gagliano et al. [13] analyzed the thermal behavior of ventilated roofs with varying placement of thermal insulation in relation to the air gap. The Fluent software was used to study the thermo-fluid dynamic behavior of air within the roof and calculate heat fluxes. Their results showed that roof ventilation can significantly reduce heat flux (up to 50%) during the summer season.

Li et al. [14] investigated numerically the effect of different influencing parameters, such as air gap thickness, roof slope, exhaust outlet size and absorption coefficient, on the thermal performance of naturally ventilated roofs. The results show that the effect of ventilated layer on the temperature delay of roofs is strong. The air layer thickness, roof slope and exhaust outlet size also play an important role in the thermal performance of ventilated roof.

Ramos and Aires [15] have carried out an experimental study of a small-scale prototype of a typical dwelling house, comprising a ceramic tile roof with vented eaves and insulated sub-tile panels. The thermal performance of this roof was evaluated under real-world weather conditions through continuous measurement of air velocity within the air gap, air temperature, and surface temperature of all roof layers.

In summary, previous studies have generally found that the ventilation of building facades and roofs can enhance energy efficiency by reducing the heat gain in buildings, and can improve indoor air quality by promoting better air circulation, which leads to greater thermal comfort.

However, the majority of research has been focused on pitched gable roofs, leaving concrete slab flat roofs-which are the dominant type of roof in Algeria-understudied. Thus, there is a need for more research that specifically investigates the effectiveness of different ventilation strategies for flat roofs in reducing heat gain and promoting energy efficiency as well as compare them to pitched roofs.

Moreover, Abdel Razek et al. [16] have demonstrated that adding a false ceiling can help reduce the cooling load of the living spaces. This highlights the potential for complementary strategies that can be used in conjunction with roof ventilation.

In the present work, the influence of the natural convection ventilation of the space between the roof and the false ceiling on the distribution of the temperature in a room is examined experimentally in the case of flat and pitched roofs. It was found that roof ventilation has a positive impact on room temperature by reducing the maximum temperature reached during solar radiation in the daytime, mitigating the effect of the roof slab's thermal load, and promoting faster cooling of the room in the absence of solar radiation at night. This effect is more significant in the case of a pitched roof.

After the abstract and introduction, this paper is structured into two main sections. The first section provides a detailed description of the experimental setup, including the materials and methods used to carry out the research. The second section presents the results of the study and provides analysis and discussion of the findings. Finally, the paper concludes with a summary of the key insights and suggests potential avenues for future research.

2. EXPERIMENTAL SET-UP

The purpose of this experimental work is to investigate the effect of natural convection of ambient air on the evolution of temperature in a room whose upper wall is subjected to a constant heat flux in the case of flat and pitched roof.

The room as shown in Figure 2 is a square based parallelepiped of side 750 mm and height 870 mm. This choice of dimensions is dictated by the construction costs and the possibility of manipulation. The side walls and floor, 12 mm thick, are made of chipboard with low thermal conductivity.

The ceiling consists of a reinforced concrete slab 45 mm thick and weighs about 90 kg, its upper face is provided with a groove housing two electrical resistances connected in parallel to the electrical network for heating the room. A 30 mm thick plasterboard is placed at 200 mm below the slab, acting as a false ceiling and thus creating two spaces: the space between false ceiling and slab (ventilated space) and the space between the false ceiling and the floor (habitat). The study of the temperature field in the latter is the purpose of this work.

The ventilated space is equipped with 18 windows of 40 mm diameter. Nine are cut in one of the sidewalls and are connected to PVC tubes, with the same diameters and of 700 mm length each, the others in the opposite wall are also connected to tubes of the same type and of 1200 mm length each.

The supply tubes are used to bring fresh air, and the others are used to evacuate hot air from the ventilated space. The supply tubes are connected to a PVC tube with a diameter of 110 mm and a length of 1200 mm.

The heating is provided by two 50 Ohm electrical resistances, connected in parallel on the network and dissipating a power density of 2844 watt/m^2, a value that seems to be greater than solar irradiance in the hottest areas in Algeria.

But this flow is not fully transmitted to the slab due to the fact that there are radiation and convection heat loss. Temperature measurements in the thickness of the slab have permitted the estimation of the average heat flux transmitted to the ventilated space to be about 380 w/m^2.

Some characteristics of some materials similar to those used in this work are given in Table 1.

Ten thermocouples, as shown in Figure 3, are used to monitor the temperature evolutions of different points of the room over time. Four are placed on the vertical, passing through the middle of the room: one at 1mm above the plasterboard and the other three at 1, 30 and 250 mm from it, the indicated temperatures are respectively designated by θ1, θ2, θ3 and θ4. Three are located on the vertical median line of the inner face of the wall S, at 30, 250 and 680 mm of the plasterboard and indicating the temperatures θ5, θ6 and θ7 respectively. Three others are located at the inlet of the hot air evacuation tubes placed at 155, 350 and 575 mm and indicating respectively the temperatures θ8, θ9 and θ10. An eleventh thermocouple takes the ambient temperature θ11. Computer using the LabVIEW Acquisition Software and Interface (NI-DAQ9213) automatically takes measurements of the first ten thermometers. The thermometers are inserted through small holes in the sidewall of the room. The holes are then carefully sealed to prevent any heat loss, which can potentially impact the temperature readings. In addition, the thermometers at the center of the room are attached to a support to keep them in their designated positions and prevent any accidental movement during the experiment.

Table 1. Characteristics of some materials

Materials	Concrete	Plaster	Chipboard Wood
Thermal conductivity K (w/m*k)	0.8-1.28	0.4	0.13-0.2
Heat capacity CP (kJ/kg*k)	0.79	4.77	0.29-0.48
Density ρ (kg/m^3)	2200-2500	800-1300	500

Figure 2. Above and side views of the room

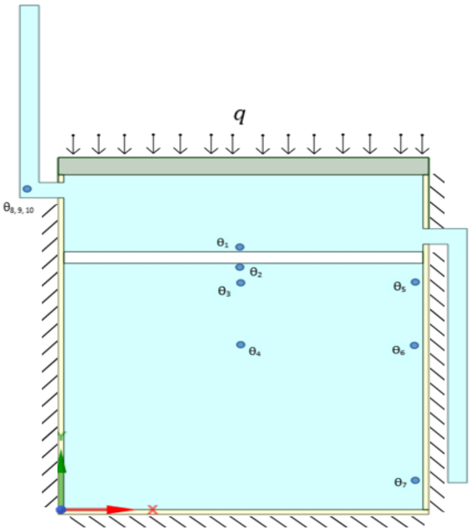

Figure 3. Positions of the thermocouples used to monitor the temperature in the room

Figure 4. Side view of the room after pitching the roof

After conducting the experiment using the room with the flat slab roof, the same room is modified by extending one the sidewalls to pitch the roof by 15° and then relocating the evacuation tubes on that new extended sidewall (Figure 4).

The experiment is conducted for the following cases:

- Case 1: Flat Roof with All the supply and evacuation tubes are closed, to be used as a reference.
- Case 2: Flat Roof with Natural convection with all the supply and evacuation tubes opened.
- Case 3: Pitched Roof with all the supply and evacuation tubes closed.
- Case 4: Pitched Roof with Natural convection with all the supply and evacuation tubes opened.

In the first case, a flat roof with no natural convection ventilation. As soon as the resistances are connected, the temperatures are taken. When the temperature θ2 reaches 40°C, the resistances are disconnected and the acquisition of temperatures continues until they become relatively close to the ambient temperature.

For the other cases the resistances are connected for the same amount of time that it took θ2 to reach 40°C in the first case, then the resistances are disconnected and the acquisition of temperatures continues until they become relatively close to the ambient temperature.

3. RESULTS AND DISCUSSIONS

In this work, we examined the effects of natural convection on temperature evolution over time in the ventilated space and the living space in a room for both flat and pitched roof cases. The following are the main observations:

For the same amount of time that took the temperature to reach 40°C (At the measurement point 1 mm below the false ceiling shown in Figure 5) in the case of a flat roof with no convection, the temperature reached only 38.7°C, 37.6°C and 35.2°C in the cases of the flat roof with natural convection, the pitched roof with no natural convection, and the pitched roof with natural convection, respectively. This demonstrates that a pitched roof allowed less heat energy to reach the false sealing and that ventilation effectively reduced the heat energy coming from the roof towards the false ceiling. It also shows that the combination between the pitched roof and the natural convection ventilation had the greatest impact.

After the heating is stopped, all the temperatures continue to increase until reaching their maximums then they decline with decreasing gradients to become almost equal to the ambient temperature after a period of time that varies from one case to another. This increase, due to the thermal inertia of the slab, is more important in the case where all the tubes are closed (without convection). For example, for the measurement point situated at 1 mm above the false ceiling (Figure 7), the temperature in the case a flat roof with no convection continued to increase after the heating is stopped from 40°C to 43°C i.e., a difference of 3°C. While for the other cases, the pitched roof with no natural convection, the flat roof with natural convection and the pitched roof with natural convection, the temperature has increased by 2.2°C ,1.7°C and 0.9°C respectively. This shows that natural convection has a positive effect in mitigating the effect of the thermal inertia of roofs.

The temperatures (θ1 and θ2) on either side of the plasterboard are very different (max difference 11℃) due to the low thermal conductivity of this plate. This emphasizes the significance of material selection in construction.

Figure 6 demonstrates that the pattern of temperature differences remains consistent as measurements progress from the false ceiling into the living space's center.

The comparison between evolutions of temperatures as a function of time for the thermocouples placed in the center and on the sidewall at 250 mm below the false ceiling, depicted in Figure 8, shows that at any time and for all the cases studied, the temperatures at the center are always higher than those at the wall. This shows that the middle of the chamber is warmer even though the walls are made of wood with low thermal conductivity and testifies to the loss of heat through the walls. This emphasizes the significance of walls isolation to avoid loss of heat in winter.

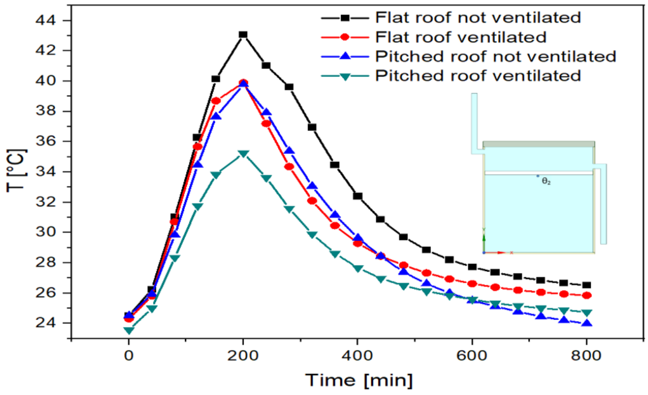

Figure 5. Evolution of temperatures as a function of time for the thermocouple placed 1mm below the false ceiling

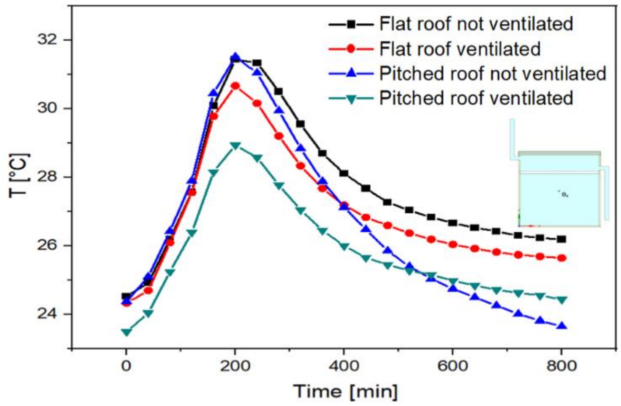

Figure 6. Evolution of temperatures as a function of time for the thermocouple placed 250 mm below the false ceiling

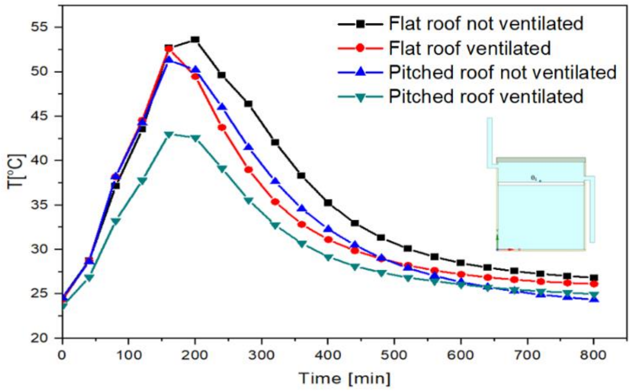

Figure 7. Evolution of temperatures as a function of time for the thermocouple placed 1mm above the false ceiling

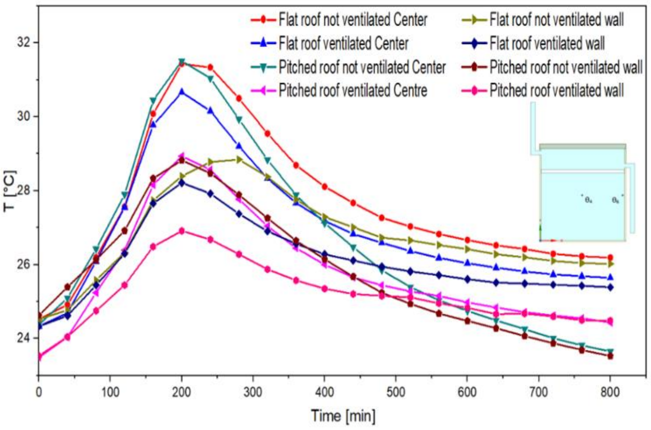

Figure 8. Comparison between evolutions of temperatures as a function of time for the thermocouple placed at the center and the thermocouple placed at the lateral wall at 250 mm below the false

4. CONCLUSIONS

Despite the difficulty of conducting experiments at constant room temperature, the study has led to numerous data showing that ventilation through natural convection of space between the roof and the false ceiling has a positive effect, decreasing the temperature in the housing space.

The findings demonstrate that roof ventilation affects room temperature in three ways, it reduces the maximum temperature that the room reaches during the period of the incoming heat flux, then it helps mitigating the effect of the thermal load of the roof and finally it leads to faster cooling of the room. This can lead to significant energy savings by reducing the amount of energy required to achieve thermal comfort.

Moreover, the results also show that the effect of ventilation through natural convection is even more significant in the case of a pitched roof. The advantages of this type of roofs should be thoroughly researched in order to provide a solid foundation for their recommendation and wider usage, particularly in countries like. Algeria where they are not commonly employed in building design.

The increase of the temperatures, even after the heating is stopped, due to the inertia of the slab, shows the importance of choosing the right materials in buildings and the importance of the proper roof ventilation.

In practical terms, this study suggests that incorporating roof ventilation in building designs, particularly for buildings located in areas with high solar radiation and high temperature differences between day and night, can lead to significant energy efficiency improvements and indoor comfort enhancement. This finding can have important implications for building managers and designers, as it highlights the potential benefits of roof ventilation and the need to consider it as a key factor in building design. Additionally, the study highlights the importance of considering local climatic. Lastly, the study's recommendations to investigate the advantages of pitched roof designs, which are currently underutilized in Algeria, can help inform future building design decisions.

However, it is important to recognize that this study had some constraints that limited its findings. Firstly, the dimensions of the room were determined based on construction costs, which could potentially affect the representativeness of the results in larger spaces. Secondly, the slight variation of ambient conditions during the experiments, such as changes in outdoor temperature, may have affected the accuracy of the data collected. Despite these limitations, the study was still able to provide valuable insights into the effectiveness of roof ventilation.

Finally, future research could include conducting numerical studies that can simulate different room sizes and building materials, allowing for more flexibility and removing the constraints imposed by construction costs. It could also focus on exploring the effectiveness of different types of roof ventilation strategies, such as passive versus active ventilation, and the optimal design and placement of ventilation systems for different roof types.

ACKNOWLEDGMENT

This work is supported by the General Directorate for Scientific Research and Technological Development (DG-RSDT), Algeria. https://www.mesrs.dz/en/dgrsdt.

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NOMENCLATURE

q	Heat flow KJ
CP	Specific heat, KJ. kg^{-1}. K^{-1}
k	Thermal conductivity, W.m^{-1}. K^{-1}

Greek symbols

ρ	Density (kg/m^3)
θ	Measured Temperatures