Thermal performance evaluation of isolation and two active solar heating systems for an experimental module: A rural Peruvian case at 3700 masl

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Abstract. Evaluation results of the thermal performance of an experimental housing module (EHM) are presented with considerations for the level of insulation and the installation of two active heaters powered by solar energy. The EHM is located in a high Andean rural area in southern Peru (latitude: 13° 45'40" S, longitude: 73° 51'26" W, and elevation: 3700 masl), where in situ measurements were made. The design and implementation of the EHM was based on the application of bioclimatic strategies and techniques. For the thermal evaluation of the EHM, 43 temperature sensors connected to dataloggers were used. The results show that the temperature inside the EHM increased more than 12 °C with respect to the outside temperature in the critical hours of extreme cold and frost when the isolation and the proposed radiative systems are used. Finally, the thermal behavior of the EHM was simulated using the EnergyPlus 8.4 program, which showed that there was an average difference of 0.5 °C between the measured interior temperature and the corresponding simulated temperature.

1. Introduction
In the high Andean areas of Peru, where elevations are 3200 meters above sea level, temperatures drop below 0 °C at dawn. While in locations above 4200 masl, the temperatures decrease even more, reaching values close to -20 °C [1]. These climatic conditions worsen in the winter months, and result in what is known as "heladas" (frosts). The heladas exceed the adaptation capacity of the poor and remote populations in the high Andes, which comprises 44.4% of the poor people in the rural areas of Peru [2]. These conditions cause damage to life, health, education, agricultural and livestock activity and infrastructure. The highly vulnerable populations, due to their social condition (poverty and extreme poverty) or their age (children and older adults), are especially affected. Moreover, because the remote location where this population lives, access by the Peruvian Government is difficult [3].

Paradoxically, these high Andean areas that experience heladas receive high solar irradiance, especially in southern Peru, where it reaches an annual average of 6 kWh·m⁻²·day⁻¹ [4]. Taking advantage of this solar resource can help improve the quality of life of the inhabitants of these areas that are strongly affected by the heladas.
Peru is a country of varied topography, with great climatic diversity and an exceptional high potential for renewable energies. However, to make the design of policies and actions to encourage the greater use of clean energies that promote the development especially in rural areas possible, it is necessary and essential to quantify the availability and the temporal distribution of renewable energy resources in the territory [5].

In this context, this article studies thermal comfort through the systematic evaluation of a two-room housing module, EHM, whose construction and evaluation was the topic of two master’s theses in Renewable Energy and Energy Efficiency [6, 7]. The EHM is located in San Francisco de Raymina, a community south of Ayacucho at 3700 masl (latitude 13° 45’40” S and longitude 73° 51’26” W); other studies have also been carried out here using the same approach to assess the thermal performance of a communal shelter [8]. The present study includes evaluation of the thermal performance of the EHM using architectural bioclimatic techniques of passive isolation, as well as the inclusion of two active radiant heaters called the radiant wall and radiant tube, which use the sun as an energy source and use water as a means of heat accumulation in the form of sensible heat.

Finally, the EHM was modeled and simulated using the EnergyPlus software, which performs dynamic energy calculations with transient heat transfer analysis. This software is owned by the United States Department of Energy and is widely used worldwide [9-11]. The EnergyPlus program [12] is supported by two other programs, SketchUp [13], in which the 3D geometry of the building is designed, and the OpenStudio interface [14], which allows the creation of thermal zones. All these programs are open source and free to use. In the present work, the EHM was simulated by generating two thermal zones: zone 1, which corresponds to the southern room, and zone 2, the northern room. For the calculation, the configuration of each construction element was used, including its thermophysical properties (obtained from tables), internal loads, window operability, and air circulation conditions.

2. Methodology
The data presented in this article are from measurements made between August 24 and October 24, 2016. Initially, only the implementation of passive thermal insulation techniques was evaluated including the isolated floor, two wooden doors, double glazed windows with wooden shutters, and the ceiling. Subsequently, the two active solar heating systems, the radiant wall and radiant tube, were included. This configuration was modeled and simulated using the EnergyPlus dynamic thermal simulation program.

2.1 Case study
The San Francisco de Raymina Community (hereinafter referred to as "Raymina") is located in southern Peru in the high Andean region and belongs to the district of Huambalpa, a province of Vilcashuamán in the Ayacucho region. Raymina has a population of approximately 40 families that participate in subsistence agriculture and livestock farming. The community can be reached by paved road up to the province, but is unpaved the rest of the way. The community has basic water and electricity services, but it has no sewage system. There is no health center, which places the population at greater risk, because people cannot be treated in time for diseases caused by low temperatures. Access to education is through an educational center up to the primary level. Figure 1a shows the Ayacucho region and its location within the map of Peru and the number of days with heladas per year in the region; figure 1b shows the solar radiation that the region receives, measured in kWh·m⁻²·year⁻¹. The gray point indicates the location of Raymina. These figures compare the need of energy for heating of houses and the availability of solar energy.
Raymina is a community with primarily adobe houses that were once roofed with “ichu” (Andean grass), which was later replaced with handcrafted tiles. Today, the use of metallic iron calamine on the roofs has become widespread, but it does not offer protection against heladas because it is a material with high thermal conductivity. Figure 2 shows a current view of Raymina where the extensive use of this material is depicted. The deficiencies in the envelope of a typical house, which causes unwanted air infiltration, can be seen in figure 2b where the red arrows show the locations of the deficiencies in the joints between the frame and door, the door and floor and the ceiling and wall.
Figure 2. Typology of the houses in San Antonio de Raymina (a) Panoramic view, where the extensive use of metallic calamine on the roofs is highlighted, (b) interior view of a house, where the lack of insulation is highlighted (gaps marked with red arrows) on doors and (c) ceilings.

In 2016, in Raymina, the average daily maximum temperature was 19.3 °C, with the high temperature of 24.1 °C, which occurred in November. Whereas the average daily minimum temperature was -2 °C, with an extreme value of -7.1 °C, which occurred during July. The average annual temperature was 9.3 °C (see figure 3). To record the solar irradiance in the area, a HOBO H21-002 meteorological micro station was installed 100 m from the EHM, and the recorded average daily solar irradiance varied from 207 to 287 W·m².
Figure 3. Climatic conditions of San Francisco de Raymina. Monthly average maximum (T_M) and minimum (T_m) temperatures, and the average monthly temperature (T_A).

The temperatures between the dashed lines in figure 3 represent what is called the comfort zone according to the Humphrey Adaptive Method [18]; here, the comfort zone is calculated for San Francisco de Raymina. This model allows the determination of the temperature of neutrality (T_n) based on the average monthly temperature T_m of each region or particular location. Subsequently, based on the comfort temperatures, the range of variability (maximum and minimum limits of the comfort zone ZC_max and ZC_min) [19] is determined. For the Raymina case, due to thermal oscillations between 13 to 15 °C, the comfort zone is ± 3 °C.

\[ T_n = 0.534 \times T_m + 11.9 \]  \hspace{1cm} (1)

\[ ZC_{max} = T_n + 3 \quad \text{and} \quad ZC_{min} = T_n - 3 \]  \hspace{1cm} (2)

2.2 Experimental Housing Module
Two independent rooms of size 3 m x 3 m with a height of 2.20 m form the EHM. The EHM has a foundation and an overlay of stone and mud; the walls are made of 0.40 m x 0.40 m x 0.10 m adobe bricks and have a 0.02 m thick layer of mud on the outside. An exterior view of the EHM is shown in figure 4, where the solar thermal collector, located on the south side of the roof, and the array of photovoltaic and solar thermal collectors on top of the water tank can also be seen.
Figure 4. View of the experimental housing module (EHM) in the community of Raymina.

The architectural techniques of passive insulation implemented in the EHM are represented schematically in figure 5 where the constructive configurations are detailed. The floors (bottom to top) are made of a layer of low density polyethylene of 0.2 mm thickness, a wooden framework with an air chamber of 0.05 m thickness, and a sandwich-type aluminum-zinc plywood with 0.04 m thick expanded polyurethane in its center. The metallic sheets provide mechanical strength to the floor (see figure 5a).

Each room has two windows facing east and west, with a 0.5 m thick wooden frame and a 3 mm double glazing, with inward-facing solid wooden shutters of 0.02 m thickness that are 0.10 m apart from the interior glass surface. The shutters are closed between 6:00 p.m. and 06:00 a.m. to avoid heat loss during the night (see figure 5b).

The doors of each room are made of plywood with a 0.032 m thick interior air chamber. Each room has two doors, one behind the other, separated by 0.65 m, which creates an internal lock-like environment. The lateral sides of the doors are adobe walls and wooden boards that close this kind of lock (see figure 5c).

The roof is made of two 0.5 mm thick aluminum-zinc iron sheets that are inclined with a profile structure as support. There is a ceiling of aluminum-zinc plywood with 0.04 m of expanded polyurethane in the middle. The space between the roof and the ceiling forms an air chamber for insulation (see figure 5d).
Finally, each room has an active solar heater installed that uses water as a sensible heat storage medium. The northern room has a radiant tube installed as shown in figure 6a, which is built from a 6-inch diameter PVC pipe has a water capacity of 65 liters. The pipe is connected with other pipes and valves of 0.5 inches to a box-type solar collector with a 75-liter capacity. The same water circulates throughout the system based on the support of a photovoltaic pump powered by a 50 W PV panel that is coupled to a 65 Ah battery and a 10 A controller, which are all at 12 V. Between 6:00 a.m. and 6:00 p.m. the system has water in the collector that serves as a heat accumulator. At 6:00 p.m., the water is discharged manually to the tube where it remains until 6:00 a.m. the next day; during this time, it serves as a kind of natural radiator as the water loses its heat to the environment. Finally, at 6:00 a.m., the water is discharged manually from the pipe into an underground tank where subsequently, with the support of the pump, it is transferred back to the box-type solar collector. This procedure is carried out daily with the control of bypass valves.

The northern room has the installed radiant wall (see figure 6b) that, unlike the radiant tube, operates automatically as long as there is a temperature difference greater than 5 °C between the temperature of the output of the solar pool type solar collector of polypropylene, located on the roof, and the indoor temperature. This system is supported by a 30 W pump that recirculates the water, along with antifreeze, from the solar collector to the tubes attached to the inner wall of the EHM. These tubes are covered with a layer of mud, 3 cm thick, and are a component of the radiant wall.

Figure 5. Schematic of the insulation applied in the elements of the envelope: (a) floor, (b) window, (c) door and (d) roof. All the measurements are in meters.
Forty-three temperature sensors, coupled to 13 dataloggers, are installed and programmed to record the indoor climate condition data every half hour.

2.3 EnergyPlus: Dynamic thermal energy simulation program

EnergyPlus accepts a variety of input variables which includes the weather file in EPW format, the location of the building, the control calendar, the simulation control, materials with their thermophysical properties, construction components, details of surfaces and subsurfaces, infiltrations or air exchanges, and internal loads (people, equipment, etc.). The program yields a variety of output variables, which include: indoor temperature and relative humidity, solar radiation per m\(^2\) of the interior and exterior surfaces, thermal transmittances, and loss and gain of energy per constructive element.

For the modeling and simulation of the EHM, two thermal zones are considered: zone 1 (Z1) in the southern room and zone 2 (Z2) in the northern room, as shown in figure 7.

![Diagram of the radiative systems used for heating the inside of EHM: (a) radiant tube and (b) radiant wall.](image)

**Figure 6.** Diagrams of the radiative systems used for heating the inside of EHM: (a) radiant tube and (b) radiant wall.

![Experimental module: (a) representation of the thermal zones and (b) the model developed with the SketchUp program used in the simulation.](image)

**Figure 7.** Experimental module: (a) representation of the thermal zones and (b) the model developed with the SketchUp program used in the simulation.
3. Results and discussions
The results presented graphically in figure 8 show the thermal behavior of the EHM for different configurations, where the use of shutters (CV), doorways (CP), and heating systems (SC) varies by configuration, as shown in Table 1.

Table 1. Configurations used in the two areas of the EHM.

| Configurations used in both environments (Z1 and Z2) of the EHM | Date    |
|---------------------------------------------------------------|---------|
| 1. Without using CV and CP No SC                              | 12-24   |
| 2. Using CV and CP No SC                                       | 27Aug-  |
| 3. Control of CV and CP Yes SC                                 | 24Sep-  |

Figure 8a shows the period when both rooms were closed (Configuration 1), but the shutters and backdoors were not used. It can be observed that in the early hours of the morning and especially at 5:30 am, the outdoor temperature was approximately 1 °C, while at the same time, the indoor temperature was approximately 10.6 °C in Z1, and 11.4 °C in Z2. However, the external thermal amplitude was 15.7 °C, while the interior temperatures of Z1 and Z2 were 5.5 °C and 4.5 °C, respectively; there is a thermal damping of more than 10 °C in both zones, with a thermal delay of 2.5 hours.

The temperatures corresponding to Configuration 2 are presented in figure 8b, in which both environments were closed, the CV and CP were closed and SC was not used. In this case, it was observed that the outside temperature was 3 °C and the interior temperatures of Z1 and Z2 were 11.1 °C and 12.1 °C, respectively. The external thermal amplitude was 12 °C, while the temperatures of Z1 and Z2 were 2.7 °C and 2.1 °C, respectively. The thermal damping was approximately 10 °C, with a thermal delay of 1.5 hours.

In Configuration 3, a control of the window shutters and back doors was applied to avoid heat losses during the night and early morning hours; there were also the two radiant systems in operation. During the evaluation of this configuration, the lowest outside temperatures were observed, with an outside temperature of -2 °C and the interior temperatures of Z1 and Z2 were 10.5 °C and 12 °C, respectively. The thermal amplitudes of the exterior and the interiors for the Z1 and Z2 were 16.4 °C, 4.5 °C and 3.6 °C, respectively, the thermal damping was greater than 12 °C and the thermal delay was 1.5 hours.
Figure 8. Mean hourly ambient interior temperatures of the southern (T_{Z1}), northern (T_{Z2}), and the outside temperature (T_{ext}). (a) EHM without shutters or doorways, (b) EHM completely closed, and (c) EHM with solar heaters.

Additionally, the thermal behavior of room Z2 in the EHM was simulated using EnergyPlus 8.4. For the simulation, the climate file was entered from the data collection in a year’s field, the materials and their thermophysical properties including density, thermal conductivity and specific heat, and the configuration of the constructions was created for each constructive element. The internal temperature for the thermal analysis was defined as the output variable, and the measured and simulated temperatures had an average difference of 0.5°C, which validates the model. As shown in figure 9, a better agreement between these values is observed after 7:00 p.m. until 8:00 am, which is when the tube behaves as a radiator. While at other times, the actual interior temperature is below the simulated one, which indicates that heat is lost. This may be due to heat transfer from Z2 to Z1, because both rooms share the wall that supports the radiant systems.

Figure 9. Average hourly temperature for zone 1, real (T_{REAL}) and simulated (T_{SIM}), and external (T_{ext}).
4. Conclusions
The results of this study showed that the temperature difference between the interior and exterior increases by more than 12.1 °C are reached in the critical hours of low temperatures. However, this increase is not enough, considering that the interior temperatures during these hours stay below the minimum limit of comfort according to the adaptive model. During the daytime, the behavior of the temperature is adequate, given that it is within the comfort zone. Therefore, it is necessary to further improve the insulation to reduce infiltration. Additionally, some other heat source by direct or indirect solar radiation may be added, such as skylights in the roof and false ceiling, or a greenhouse facing east and west.

The radiant tube heater, due to the simplicity in its construction and cost, is an innovation that is easily replicated in the Andean zones compared to commercial radiant wall heaters, which are more costly than radiant tubes. In addition, the results showed that the tube type radiator provides temperatures that are 1.5 °C greater than the radiant wall.

Adobe, a traditional construction material in Andean areas, improves the interior temperature of houses because the interior temperature is damped, thus heat is preserved in the interior.

The dynamic thermal simulation, once validated, can help to interpret the results and to define new changes to improve the internal conditions.

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