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Design of a “Test Cell” to be located at 4500 masl in a high Andean region of Peru and dynamic simulation of the thermal performance of housing wall materials

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Abstract. The objective of the present study is to select appropriate wall materials for houses in high Andean regions based on the measurements of the thermal behavior of construction materials using a “Test Cell” under real environmental conditions. It will be the first “Test Cell” to be installed in Peru, in Imata-Arequipa, at 4500 masl. The design and thermal analysis of the “Test Cell” are presented using dynamic simulations with the *EnergyPlus* program. Initially, the thermal performance of adobe, a traditional construction material in rural regions of Peru, is simulated using real meteorological data recorded in Imata between August 18 and 24, 2018, a period with low temperatures (-12.6 °C).

1. Introduction

In Peru, especially in the High Andean areas, the vernacular materials of traditional building walls are blocks of soil, such as adobe and “tapial”, and stones of high thermal masses and thicknesses of 0.40 to 0.50 m. Empirically, it is known that these materials contribute to shielding the interior of the houses from the low outside temperatures due to the thermal properties of these materials. However, in the case of Peru, the quantification of these properties is still incipient. In the present study, it is proposed to determine, in situ, the thermal transmittance and thermal-energetic behavior of vernacular and conventional materials used in housing walls under real environmental conditions of a high Andean zone. For this purpose, it is proposed to design, build, characterize and monitor a “Test Cell” [1]. The study also contemplates, from the conception of the design, the use of the dynamic thermal/energy calculation simulation software *EnergyPlus* [2], as presented in the present study, considering real meteorological data recorded in the place where the “Test Cell” will be built. In subsequent works, once the “Test Cell” has been constructed and the measurements carried out, the validation of the model will be presented.

Given that the specialized literature does not report work with a “Test Cell” in Peru, this work would be the first in Peru with a “Test Cell”, and even, given the height at which it will be implemented, in the village of Imata in the Arequipa region at 4500 meters above sea level (Lat. 15 ° 55'43" S, Long. 71 ° 06'31" W), it can be assumed that it would be the first worldwide at this altitude. Imata is considered the coldest area in the Arequipa region and the third coldest area in Peru, where temperatures have been recorded down to -23 °C [3]. Annually, the population of Imata, like at other places with similar altitudes, suffers the onslaught of low temperatures or “heladas” (decrease of the temperature below 0 °C), affecting their health and even their lives. Paradoxically, the high Andean areas are blessed with a high amount of solar energy of, on average, more than 6 kWh·m⁻²·day⁻¹ [4].



The “Test Cells” have been and are being developed and studied mainly in Europe since the mid-1980s through the PASSYS (Passive Solar Elements and Systems Testing) project of the European Community [5, 6]. Their characteristic is that they are built in the open field and their evaluation is carried out under real environmental conditions. They have a high level of insulation (low thermal transmittance) and airtightness in the floor, ceiling, and three walls, with the fourth wall (facing south in the Northern Hemisphere and, in our case, facing north) being the interchangeable test element or wall that is constructed with the materials to be characterized to determine its thermal properties, such as its heat capacity and thermal transmittance in the case of opaque materials, and the solar radiation energy gain through transparent materials. In this project, 12 countries and approximately 60 researchers participated, building a total of 35 “Test Cells”, initially evaluating wall materials, then ceilings, and lately elements integrated into the walls, such as windows, photovoltaic panels, green walls and roofs. Over the years, the PASSYS denomination passed to PASLINK [7, 8] and currently to DYNASTEE (Analysis, simulation and dynamic tests applied to the energy and environmental performance of buildings) [9].

In Mexico, studies were also conducted with “Test Cells” with the aim of evaluating the behavior, contribution and thermal performance of materials, comparing those of traditional use, such as “tapial”, with others of a conventional nature, such as concrete [10] and materials commonly used in urban constructions, but with different construction layers [11].

Although in Peru, there is no experience of characterizing the behavior of building materials in the open air and in the high Andean area, there are local studies regarding bioclimatic constructions. In these works, local materials, representative of the area, such as adobe [12], tapial, wood, ichu, and totora [13, 14], were used to determine, by means of a passive design, the increase in the interior temperature of homes with respect to the outside temperature. If a reasonable increase in the inside temperature was not possible to obtain with passive means, active techniques with solar energy were used [15].

Based on the local experience with bioclimatic constructions and the international experience with “Test Cells”, a “Test Cell” will be constructed with a purely wooden skeleton and conventional materials for its insulation, with thermal transmittance values on its envelope of the order of $0.0X \text{ W}\cdot\text{m}^{-2}\cdot\text{C}^{-1}$. For the calculations and thermal/energy analysis, the dynamic calculation engine of the *EnergyPlus* program, developed by the Department of Energy of the United States and of recognized worldwide application, will be used. This software uses as input data the density, specific heat, and thermal conductivity of the materials for the analysis of transient heat transfer. In climates where the daily thermal oscillation is high and the solar radiation is considerable [16], as presented in the high Andean regions, the thermal analysis in steady state, considering only the thickness and thermal conductivity of the material of the walls, as considered in the Peruvian Technical Standard EM.110 “Thermal and Light Comfort with Energy Efficiency” [17], does not allow the determination of thermal well-being or energy savings. In these cases, it is also necessary to consider the energy storage capacity (thermal inertia) of the building materials [18], as does *EnergyPlus*. The modeling and simulation with *EnergyPlus* will be validated with experimental data measured at the “Test Cell” [19, 20].

This study presents the design and analysis of the “Test Cell” as a result of modeling and simulation using *EnergyPlus*. Preliminary for this study, adobe is considered an interchangeable wall material since it is a representative material for Imata. Real meteorological data, recorded in periods of “heladas” (freezing temperatures), with a Davis weather station, Vantage Pro2 Plus, installed on site will be used for the generation of a weather file in EPW format (*EnergyPlus Weather Data*) as input to *EnergyPlus* using the program *Element* [21].

2. “Test Cell” at 4500 masl

The “Test Cell” will be built in Imata at 4500 masl, whose meteorological conditions of solar irradiance and outdoor temperature have been recorded in situ from August 18 to 24, 2018. Figure 1a shows the stereographic chart with black dotted lines for those dates, with the sun to the north. Figure 1b shows the solar irradiance on a horizontal surface and the outside air temperature, which, on average for the days of registration, were $6.1 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ and $0.7 \text{ }^\circ\text{C}$, respectively, with an extreme minimum temperature of $-12.6 \text{ }^\circ\text{C}$.

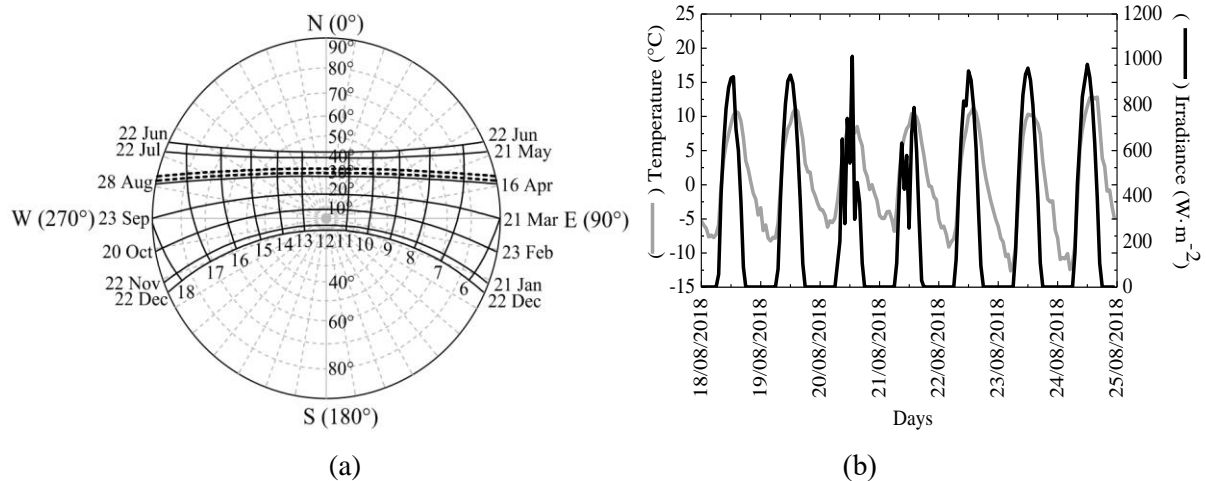


Figure 1. (a) Stereographic solar chart for the Imata village (4500 masl). Latitude: $15^{\circ} 55'43''$ S and Longitude: $71^{\circ} 06'31''$ W. (b) Solar irradiance and outside air temperature for Imata according to data recorded from August 18 to 24, 2018.

The “Test Cell” will be located in a free space of land belonging to the parish of Imata village (figure 2a) in the district of San Antonio de Chuca, Caylloma Province, Arequipa region. Figure 2b shows the parish land dimensions and the location foreseen for the “Test Cell” (red square).

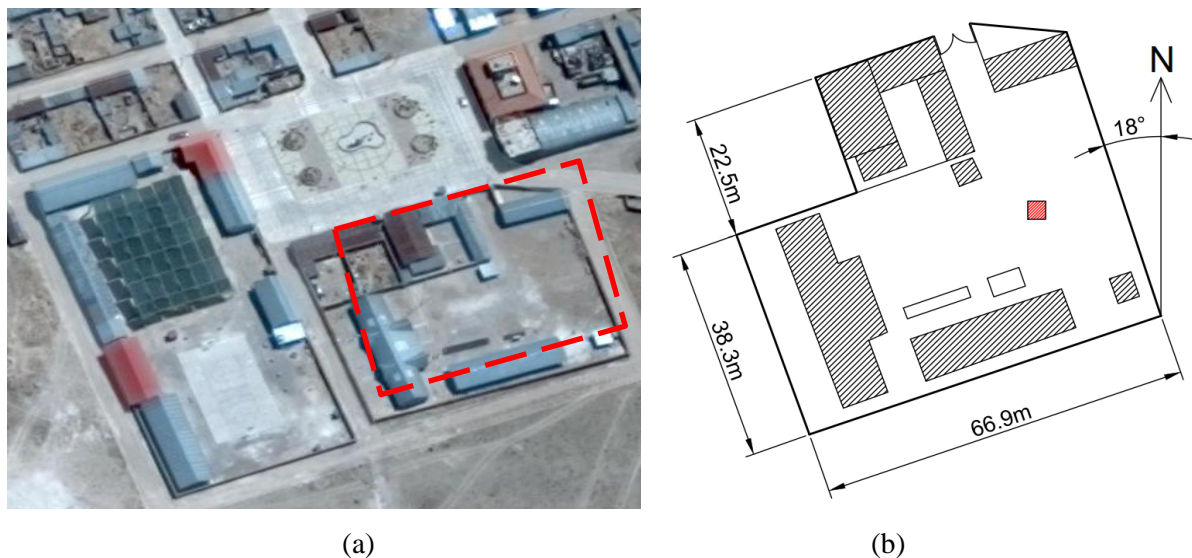


Figure 2. Parish land area in Imata (a) seen with Google Maps and circumscribed with a broken red line and (b) the dimensions and location of the “Test Cell” (indicated with a red square).

2.1 Description

The “Test Cell” will have a cubic shape and will consist of an environment with interior dimensions of $2.4\text{ m} \times 2.4\text{ m} \times 2.4\text{ m}$ and exterior dimensions of approximately $3.2\text{ m} \times 3.3\text{ m} \times 3.3\text{ m}$ (these dimensions are representative of the minimum for a habitable room). It will sit on six concrete cubes at a height of 0.3 m above the ground to prevent heat transfer between the ground and the “Test Cell”. Given the characteristics of the “Test Cell”, which must have an envelope with a very high level of insulation, the use of high-insulation materials, such as expanded polystyrene, fiberglass, and expanded polyurethane, will be used for the floor, ceiling and walls facing east, west and south. The north-facing wall, as a test wall, will be made of adobe and interchangeable. (The project also includes, later on, the characterization of other materials, such as ignimbrite “sillar”, solid clay brick, and prefabricated drywall panels). Access

will be through a double door. Table 1 shows the thermal transmittances (U) of the different elements of the envelope, on the order of $0.0X \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$, calculated according to a stationary heat transfer regime. The values of the thermal properties of the materials have been taken from the Peruvian Technical Standard EM.110, with values of surface convection heat transfer at the walls (inner, h_i , and outer, h_o) of 9 and $16.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$, respectively, and for the roof, h_i and h_o of 11.1 and $20 \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$, respectively, and for the floor, h_i and h_o of $11.1 \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$, respectively. The inverses represent the inner ($1/h_i$) and outer ($1/h_o$) surface resistances, which for the calculation of U , the total resistance per construction component is $1/h_i + 1/h_o$, with data also taken from the EM.110 standard for the high Andean bioclimatic zone.

The skeleton structure of the “Test Cell” will be entirely moisture resistant wood to avoid deformations and thermal bridges; it will have the characteristic of a prefabricated construction, light and detachable, where the fasteners will be made with pulls according to the dimensions of the wood. It will have two plywood doors, each with 0.1 m of expanded polyurethane insulation and separated 0.60 m from the other (exclusive type) to decrease the air flow. The roof material has a sandwich configuration of galvanized calamine veneers at the ends, with the surface to the outside grooved and the other flat, and inside it has 0.05 m-thick expanded polyurethane.

The interchangeable wall (figure 3a) will be oriented to the north, as seen in figure 3b, given that at the latitude of Imata, the path of the sun during most of the year will be more north and the effect of solar radiation on its surface determines the thermal input to the inside of the module. The adobe bricks to be used will be $0.4 \text{ m} \times 0.4 \text{ m}$ at the base and 0.1 m high. The details of the adobes and construction system of the wall will be carried out respecting the traditional form of construction in Imata, that is, water, earth and ichu. The mixture will be left to rest three nights wrapped in plastic so that the clay contained in the earth is saturated with moisture and it does not suffer cracks while drying. The laying of the adobes will be done with the detailed mixture.

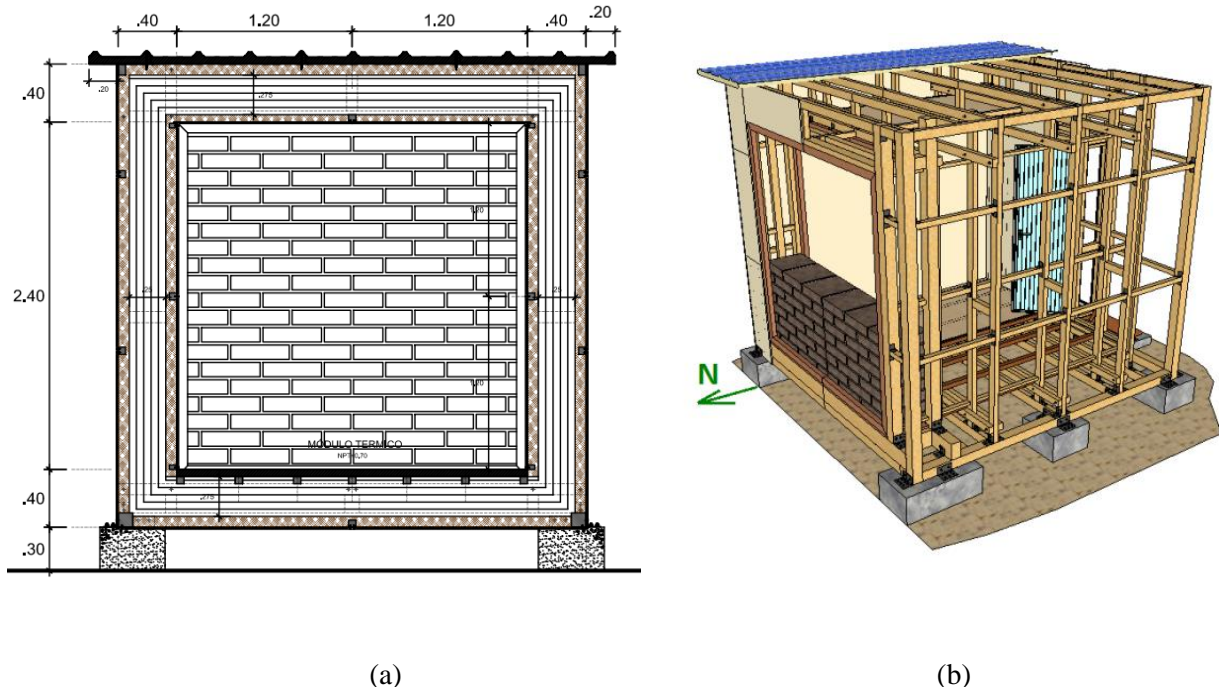


Figure 3. Views of the “Test Cell” (a) north wall with interchangeable adobe and (b) 3D design made with the program *Trimble SketchUp*.

Table 1. Thermal transmittance (U) of the constructive elements of the “Test Cell”, calculated at steady state, with values of thickness (e), thermal conductivity (k), thermal resistance (e/k), and total surface resistance (1/hi + 1/ho). The interchangeable wall materials are not included.

	Layers (from outside to inside)	e (m)	k (W·m ⁻¹ ·°C ⁻¹)	e/k (m ² ·°C·W ⁻¹)	U (W·m ⁻² ·°C ⁻¹)
Walls	Plasterboard	0.0125	0.250	0.077	0.088
	Fiberglass	0.075	0.040	1.829	
	Expanded polystyrene	0.250	0.033	7.576	
	Fiberglass	0.075	0.040	1.829	
	Plasterboard	0.0125	0.250	0.077	
	1/hi+1/ho	-	-	0.170	
Floor	Wood OSB	0.010	0.130	0.077	0.076
	Fiberglass	0.075	0.040	1.875	
	Expanded polystyrene	0.280	0.033	8.485	
	Aluzinc	5E-04	125.5	3.98E-06	
	Expanded polystyrene	0.050	0.020	2.500	
	Aluzinc	5E-04	125.5	3.98E-06	
	1/hi+1/ho	-	-	0.180	
Roof	Aluzinc	5E-04	125.5	3.98E-06	0.071
	Expanded polystyrene	0.050	0.020	2.500	
	Aluzinc	5E-04	125.5	3.98E-06	
	Fiberglass	0.075	0.040	1.875	
	Expanded polystyrene	0.270	0.033	8.182	
	Fiberglass	0.050	0.040	1.250	
	Wood OSB	0.010	0.130	0.077	
	1/hi+1/ho	-	-	0.140	
Door	Wood	0.004	0.120	0.033	0.096
	Expanded polystyrene	0.100	0.020	5.000	
	Wood	0.004	0.120	0.033	
	Air chamber	0.600	-	0.160	
	Wood	0.004	0.120	0.033	
	Expanded polystyrene	0.100	0.020	5.000	
	Wood	0.004	0.120	0.033	
1/hi+1/ho	-	-	0.170		

2.2 Modeling and simulation of the “Test Cell” with EnergyPlus

The *EnergyPlus* dynamic simulation program is a simulation calculation engine and is complemented by the *Trimble SketchUp* program [22] for modeling the design of a 3D building or house and *OpenStudio* [23], which is an interface for *EnergyPlus* where thermal zones are generated. All are open-source and free-use programs. The methodology of using these programs begins with the modeling of the 3D design and generation of the thermal zone with *SketchUp* and *OpenStudio*. Subsequently, the input and output variables are defined with *EnergyPlus*. Examples of input variables are the climate file for Imata and physical properties of the materials of the envelope: roughness, density, thermal conductivity, specific heat, solar absorptivity (0.3 for plaster and 0.75 for adobe [24]) and thermal infrared emissivity (= absorptivity = 0.9). The interior air temperature and the solar irradiance incident on the outer walls of the “Test Cell” are considered as output variables, as well as the heat flux entering or leaving the surfaces of the walls.

The simulation of the “Test Cell” is carried out considering first that the four walls are equal, with the configuration shown in table 1, as well as for floor and ceiling (flat), without door, without infiltrations, and without internal loads or operability. All walls are normal to the direction of the cardinal points. Then, the “Test Cell” is simulated with adobe in the interchangeable north facing wall, with the thermal data given in table 2. All the simulations are carried out for the period from August 18 to 24, 2018, a time of low temperatures (“heladas”).

Table 2. Thermal transmittance (U) of adobe wall, with wall thickness (e), thermal conductivity (k), thermal resistance (e/k), total surface resistance (1/hi + 1/ho) and specific heat Ce.

Material	e (m)	k (W·m ⁻¹ ·°C ⁻¹)	e/k (m ² ·°C·W ⁻¹)	U (W·m ⁻² ·°C ⁻¹)	Ce (J·kg ⁻¹ ·°C ⁻¹)
Adobe	0.400	0.950	0.421	1.692	920
1/hi+1/ho	-	-	0.170		

3. Results and discussion

From the simulation, the data of the incident solar irradiance on the outer wall surfaces of the “Test Cell” are obtained as shown in figure 4. According to the orientation, the walls received daily, on average, during August 18 to 24, 2018, the following radiation energy: 40.67 kWh on the north wall, 36.82 kWh on the west wall, 23.72 kWh on the east wall, and 10.21 kWh on the south wall. The daily average of the solar irradiance (I_o) on a horizontal surface was 254 W·m⁻² with a maximum of 893 W·m⁻² at 13 p.m.

The choice of placing the interchangeable wall facing the north was based on the previous results, given that it receives the greatest energy of solar radiation during the day, resulting in a greater thermal contribution of solar radiation to the temperature in the interior.

Simulating the indoor air temperature (T_i) of the “Test Cell” with all four walls equal and with a configuration according to table 1 (ceiling and floor configurations do not change), the graph shown in figure 5a is obtained, where the average temperature is 6 °C (0.7 °C is the outside average), with a thermal oscillation of the inside temperature (T_i) of 0.4 °C, while the oscillation of the outside temperature (T_o) was 18.4 °C. The average minimum daily external temperature was - 8.5 °C (at 6 a.m.), the simulated indoor temperature at that time is 6.3 °C, that is, there is an increase in the minimum indoor air temperature with respect to the outside of 14.8 °C.

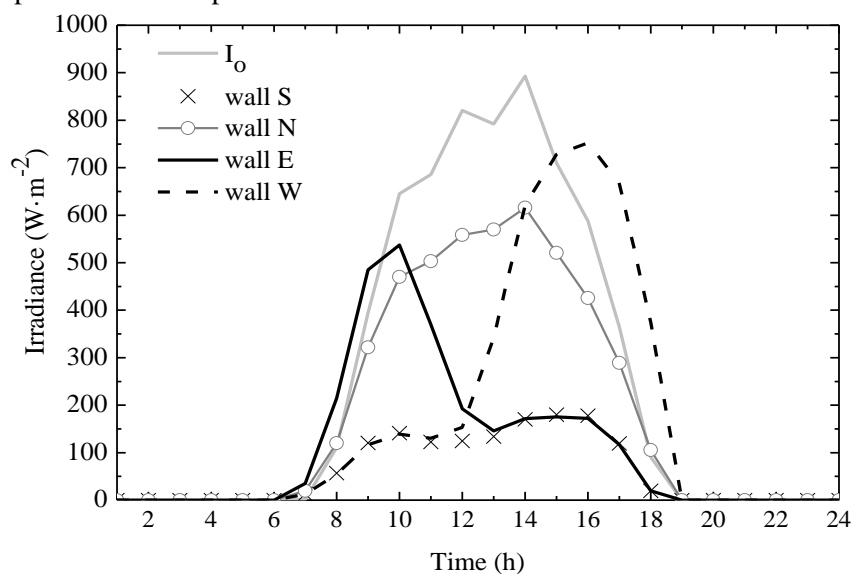


Figure 4. Recorded daily average solar irradiance on a horizontal surface (I_o) and calculated incident on the exterior wall surfaces: East (E), West (W), North (N), and South (S) walls, from August 18 to 24, 2018.

Subsequently, the “Test Cell” is simulated with the interchangeable north-facing wall with adobe and maintaining the materials of the other three walls, the floor and ceiling, according to table 1. The simulated interior temperature is shown in figure 5b.

The simulated indoor temperature, with the adobe north wall, also has a small oscillation, similar to the previous case, but a much higher average of 11.3 °C, with a maximum of 12.0 °C, at 2 to 4 a.m., and a minimum of 10.6 °C, at 15 to 17 p.m. The average indoor temperature is 10.6 higher than the average outdoor temperature, and the minimum indoor temperature is 19.1 °C higher than the minimum outdoor temperature (averaged over the period of evaluation).

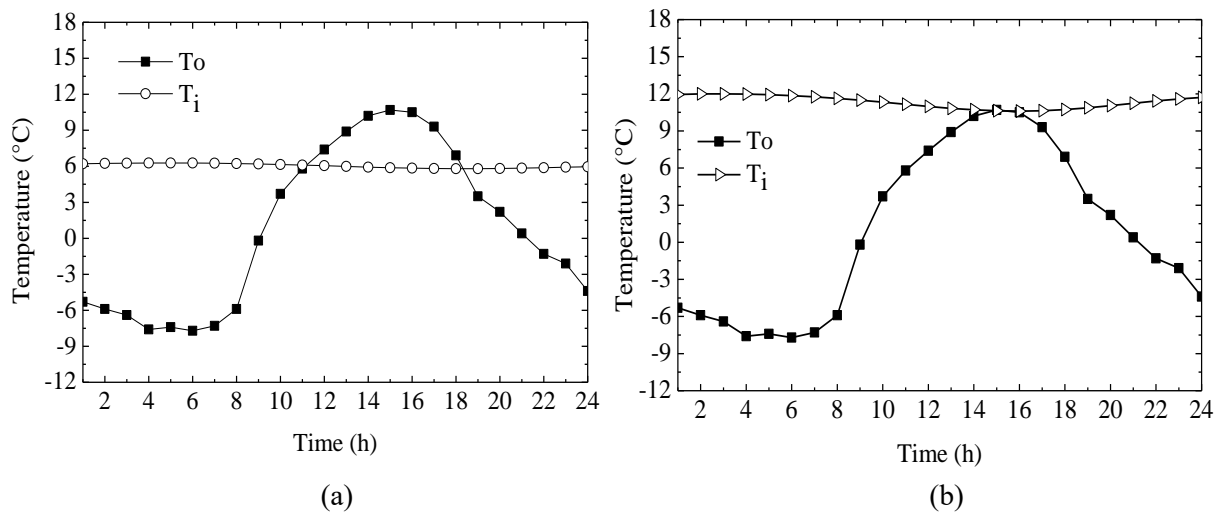


Figure 5. Mean hourly temperature simulated inside (T_i) and measured outside (T_o), considering (a) 4 equal walls and (b) north wall of adobe, for the days from August 18 to 24, 2018.

Table 3 shows the simulated daily heat flows through the adobe wall surfaces, the resulting heat flow through the adobe wall and the daily heat stored in the adobe wall. The heat coming in the wall from outside varies significantly from day to day (depending on the weather), but the heat flowing into the interior of the test cell is much more constant, indicating that the adobe wall acts as a heat storage. The average daily heat stored during the 7 days of the evaluation is -99 Wh. (in long periods, this value tends to go to zero).

Table 3. Daily heat flows through the surfaces of the adobe wall (S_i inner, S_o outer), average heat flow and daily heat stored in the wall. A positive sign denotes that heat comes out of the wall; a negative sign denotes that heat goes into the wall.

Days	S_i (Wh·day ⁻¹)	S_o (Wh·day ⁻¹)	Average (Wh·day ⁻¹)	Storage (Wh·day ⁻¹)
18-Aug.	543	-466	505	-77
19-Aug.	540	-642	591	102
20-Aug.	464	1399	-468	-1863
21-Aug.	264	447	-92	-711
22-Aug.	390	-1065	728	675
23-Aug.	544	-723	634	179
24-Aug.	573	-1573	1073	1000
average	474	-375	424	-99

Finally, the additional heating energy requirement of the “Test Cell” is calculated for the two cases considered in figure 5 if it is desired to maintain a uniform temperature of 15 °C inside the “Test Cell”

(and considering the climate of August 18-24, 2018). The results are shown in table 4. The daily energy requirement for the case with all 4 walls according to the configuration of table 1 is 6.88 kWh, and with a north adobe wall, it turns out to be 9.74 kWh.

Table 4. Heating requirement to maintain the inside of the “Test Cell” at 15 °C when all the walls are equal and when the north wall is made of adobe.

Days	Equal walls (kWh·day ⁻¹)	Adobe wall (kWh·day ⁻¹)
18-Aug.	0.95	1.10
19-Aug.	0.95	1.12
20-Aug.	0.93	1.13
21-Aug.	0.99	1.65
22-Aug.	1.00	1.75
23-Aug.	1.02	1.50
24-Aug.	1.04	1.49

4. Conclusions

With the “Test Cell”, which will be constructed in Imata/Arequipa according to the design described in this study, it will be possible to evaluate different construction materials under real high Andean climatic conditions and validate the simulations performed with *EnergyPlus*.

Acknowledgement

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