

OPTIMIZATION OF THE THERMAL COMFORT OF AN ECO-FRIENDLY HOUSE: OPEN FOAM MODELING OF SANDWICH-TYPE WALLS WITH ICHU (STIPA ICHU) INSULATION

OPTIMIZACIÓN DEL CONFORT TÉRMICO DE UNA CASA ECOLÓGICA: MODELAMIENTO EN OPENFOAM DE MUROS SANDWICH CON AISLANTE DE ICHU (STIPA ICHU)

OTIMIZAÇÃO DO CONFORTO TÉRMICO DE UMA CASA ECOLÓGICA: MODELAGEM NO OPENFOAM DE PAREDES SANDWICH COM ISOLAMENTO DE ICHU (STIPA ICHU)

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ABSTRACT

The use of sustainable materials is an important means of achieving thermal comfort in homes in cold climates. The study performs CFD (computational fluid dynamics) analysis in OpenFOAM of an eco-friendly house to optimize the sandwich-type walls (wood chipboard/stipa ichu/wood chipboard) using response surface methodology in a complete central design, to achieve thermal comfort in extreme cold environments using the PMV average vote prediction index. The evaluation collected data from an on-site weather station, validated it, simulated it, and predicted its performance at extreme cold ambient temperatures. The results indicate the optimal wall thickness for thermal comfort in the eco-friendly house at external temperatures of -10°C and -20°C , and explain the complex effects of external temperature on PMV. The study concludes by providing the optimal minimum dimensions of the sandwich-type wall (wood chipboard/stipa ichu/wood chipboard) that preserve thermal comfort.

Keywords

thermal insulation, construction materials, computational fluid dynamics, bioclimatism, rural housing

RESUMEN

El uso de materiales sostenibles es una alternativa importante para lograr el confort térmico en viviendas ubicadas en climas fríos. El estudio realiza un análisis por dinámica de fluidos computacional (CFD) en OpenFoam de una casa ecológica, con el fin de optimizar las paredes de tipo sándwich (maderba/ichu/maderba) mediante la metodología de superficie de respuesta en un diseño central completo, para lograr confort térmico en entornos de frío extremo mediante el índice de predicción de voto medio (PMV). La evaluación recogió datos de una estación meteorológica in situ, los validó, simuló y predijo su desempeño a temperaturas ambientales de frío extremo. Los resultados indican el grosor de pared óptimo para el confort térmico en la casa ecológica con temperaturas externas de -10°C y -20°C y, además, explican los efectos complejos del comportamiento de la temperatura externa sobre el PMV. EL estudio proporciona las medidas mínimas óptimas de la pared tipo sándwich (maderba/ichu/maderba) que logran preservar el confort térmico.

Palabras clave

aislamiento térmico, materiales de construcción, dinámica de fluidos computacional, bioclimatismo, vivienda rural

RESUMO

O uso de materiais sustentáveis constitui uma alternativa importante para garantir o conforto térmico em residências localizadas em climas frios. O presente estudo realiza uma análise por dinâmica de fluidos computacional (CFD) no programa OpenFoam de uma casa ecológica, com o objetivo de otimizar as paredes do tipo sanduíche (madeira/ichu/madeira) por meio da metodologia de superfície de resposta em um projeto central completo, para alcançar o conforto térmico em ambientes extremamente frios, utilizando o índice de previsão de votação média (PMV). A avaliação coletou dados de uma estação meteorológica in situ, validou-os, simulou-os e previu seu desempenho em condições de temperatura ambiente extremamente baixa. Os resultados indicam a espessura ideal da parede para o conforto térmico na casa ecológica em contextos com temperaturas externas de -10°C e -20°C , além de explicar os efeitos complexos do comportamento da temperatura externa sobre o PMV. O estudo fornece as medidas mínimas ideais para paredes do tipo sanduíche capazes de preservar o conforto térmico.

Palavras-chave

isolamento térmico, materiais de construção, dinâmica de fluidos computacional, bioclimatismo, habitação rural

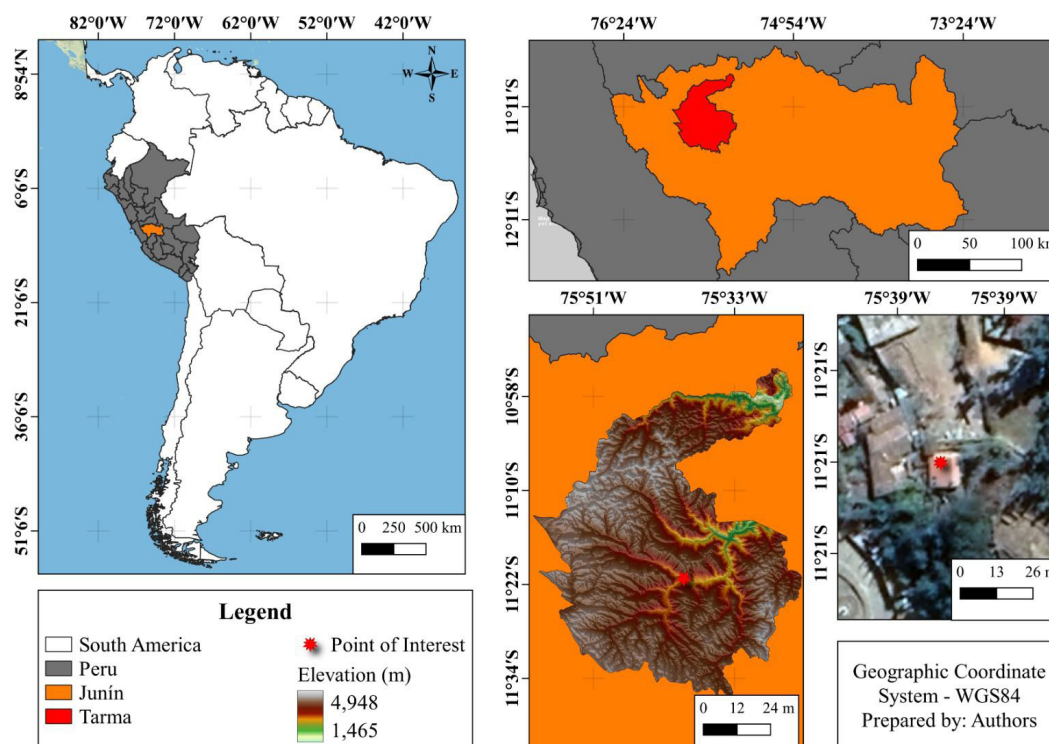


Figure 1. Location of the experimental unit: Eco-friendly house in Muruhuay, Peru. Source: Prepared by the authors.

INTRODUCTION

Thermal comfort is a key factor in ensuring suitable living conditions and reducing energy demand in homes in cold climates, especially in high Andean regions, where temperatures can drop dramatically at night. Conventional homes in these areas often have thermal insulation problems, increasing their reliance on heating sources and leading to elevated heating costs (Marchante González & González Santos, 2020). These energy costs lead to so-called energy poverty, whose effects on the health and economy of the inhabitants are widely documented (Hills, 2012).

Using sustainable, locally sourced materials is an effective means of improving the thermal performance of buildings (Ortiz Caicedo et al., 2023). For instance, the ichu (*Stipa ichu*) can be found in the high-altitude Andean regions of Peru and Bolivia. It is an indigenous grass of the Andes that grows at altitudes above 3500 m.a.s.l. and is a key resource for construction, livestock feed, and soil conservation. The ichu grows in poor soils and in low-humidity conditions, tolerates extreme temperatures, from frost to intense solar radiation, and is resistant to strong winds and precipitation (Charca et al., 2015). Its fibers are light, flexible, and easy to handle; they are hollow, which allows the static air core inside to confer low thermal conductivity, as they act as micro-thermal barriers that reduce heat transfer by

conduction, resulting in reduced heat loss in cold climates (Frías et al., 2020; Piñas et al., 2020).

Despite its benefits, the use of ichu in construction still presents challenges, especially regarding optimizing its thickness. The lack of detailed technical studies has limited its application to traditional construction and has failed to provide quantifiable efficiency criteria. Hence, it is necessary to analyze its thermal behavior using advanced tools that evaluate its performance in different configurations. This study proposes optimizing thermal comfort in eco-friendly houses by varying ichu wall thickness through CFD (Computational Fluid Dynamics) simulations (Moreno-Casas et al., 2020).

METHODOLOGY

The research follows a path that starts with on-site measurements (temperature and humidity) before implementing the model and verifying the simulation's accuracy. Validation is then conducted using the average absolute error index between the CFD Model and reality. After that, a statistical design is used to analyze simulation data on external temperature and wall thicknesses to calculate PMV and optimize thermal comfort using the Response Surface Methodology (RSM).

The eco-friendly house used for the thermal comfort

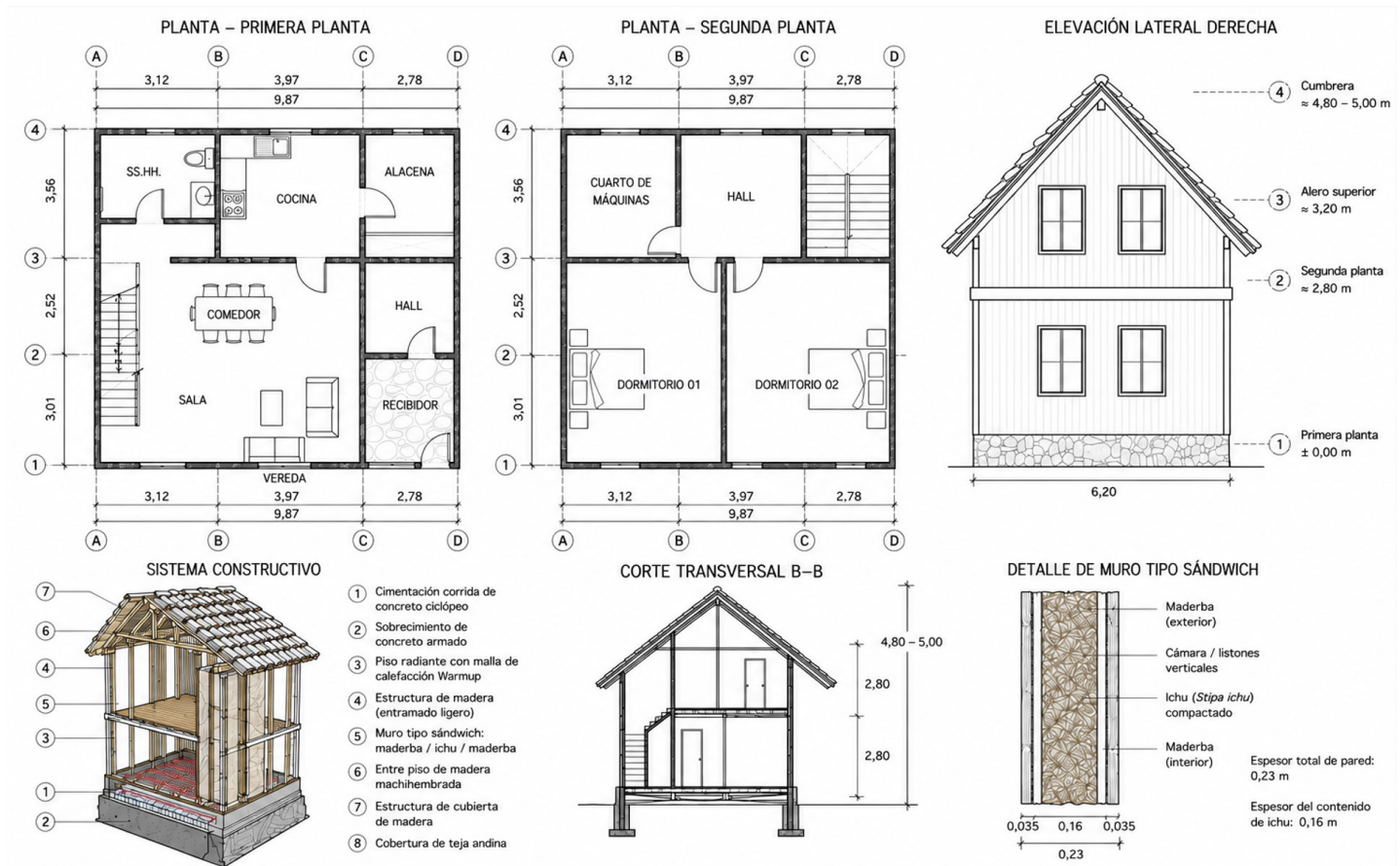


Figure 2. Constructive diagram of the house under study. Source: Prepared by the authors.

analysis and the model's validation is located in the Muruhuay Village Center of Tarma, Peru, at coordinates -11.347435 N, -75.652674 E (Figure 1).

The house under study is a sustainable two-floor construction. The first floor consists of a living-dining room, kitchen, bathroom, hall, and storage room. The second floor has two bedrooms and a machine room. Built with a huayruo wooden structure, it is reinforced with steel supports and has 23-cm-thick sandwich-type walls (chipboard/ichu/chipboard) and doors. The ichu collected was physiologically mature and naturally dried at room temperature, with a moisture content matching the ambient environment (8-12%). The house has a radiant floor heating mesh set on a chip bed. Its roof features an Andean tile ridge, with a triplay ceiling below (President of the UNAT Organizing Committee, 2017). The indoor heat flow dynamics rise during the day and fall at night. The research assumes the house is north-facing, has double-glazed windows, and represents a real house. Figure 2 shows the house's schematics.

The scenarios consisted of performing steady-

state simulations representing the most critical cold nighttime conditions, matching the extreme design values for the Andean Highlands during the winter solstice, the period with the lowest temperatures and zero solar radiation. Wall thicknesses from 7.75 cm to 57.2 cm and external temperatures from -27.4 °C to 15 °C were evaluated. Two fixed 15-cm-thick layers of wood were used to maintain constant thermophysical properties, with the ichu core thickness as the variable parameter (ranging from 4.75 cm to 54.2 cm). No other changes were made to the house's structure.

DEVELOPMENT OF A CFD THERMAL COMFORT MODEL IN OPENFOAM

Thermal comfort is the psychological state that reflects one's satisfaction with the thermal environment (Fanger, 1970), and it can be predicted using environmental predictor variables. Meteorological data were collected daily by the meteorological equipment (RK 900 05 RIKA) at 15-minute intervals for 4 months (December 2025 and January, February, and March 2026). The sensors outside the house were placed 3.78 m from the floor, parallel to one of the north-facing windows, and the indoor sensor was

placed 1.5 m above the floor in the central part of the main hallway on the ground floor. These locations had already been used by Marchante González & González Santos (2020) to assess the effects on people of average height and to evaluate winds and thermal cycles at the study unit's location. The sensors sent data to a wireless data logger, which was then exported to CSV format for processing. From these, representative samples were used to design the CFD model. The data were validated according to the standard metrics to evaluate the difference between CFD and field measurements, using the mean absolute error (MAE) indicator, which was 10.6%, for the sample of 40 y observations ($y_1, \dots, y_n$) and 40 predictions (Hodson, 2022). After that, the data processing consisted of determining the walls' thermal conductivity index using the house's actual data. Using these data, the simulations were run, including PMV calculations and optimization following the experimental design.

The numerical domain in OpenFOAM was generated using blockMesh, and a control volume was defined to represent the cross-section of the sandwich-type wall. For the minimum resolution for numerical stability, the criteria of Tominaga et al. (2008) were applied; the domain was divided into three functional blocks along the X-axis, corresponding to the physical layout of the house (wood chipboard/ichu/wood chipboard). Each block was discretized at the outset with a base mesh of 10x10x10 cells, ensuring sufficient node density at each stage. Accurate capture of thermal gradients at the interfaces was achieved by selecting a higher level of refinement (1 - Advanced Refinement), which increased resolution in areas with thermal transitions. The calculations were performed using the second-order linear Gauss scheme and an implicit Euler temporal scheme; as a result, the energy equation was monitored, reaching an absolute residual of 10^{-6} , which was sufficient to ensure the stability and validity of the thermal results.

It is necessary to point out that the CFD simulation considered an architectural envelope with high hermeticity. Infiltrations through joints or ventilation grilles were omitted to evaluate the maximum insulation potential of the ichu panel, thereby avoiding interference from losses. In this way, the flows created exclusively obey the density gradients, moving the air from a lower to a higher floor.

NUMERICAL DETAILS OF THE SIMULATION

A structured mesh comprising hexahedral cells and 3 functional blocks (sandwich-type wall layers) was used for the spatial discretization. The numerical schemes included: the Euler time derivative; the Gauss-linear gradients; and the Laplacian via the

corrected Gauss-linear (a second-order scheme that corrected for the mesh's non-orthogonality). A linear interpolation (interpolationSchemes), i.e., of the second order, and the gradient on the faces (snGradSchemes) normal to the faces, corrected for non-orthogonality, were used. A tolerance of 1×10^{-6} and a RelTol (relative tolerance) of 0 was used in addition to the Convergence criteria (fvSolution), for the temperature (T) solver. The solver iterated until the temperature equation residual was reduced to below 10^{-6} (in absolute value), ensuring numerical stability and physical consistency.

The boundary and initial conditions were determined using the 0/*T and blockMeshDict files. The former (border section in blockMeshDict) was specified for the atmosphere (patch type) to group the outer faces where the fixed-temperature condition is applied. The specific faces are defined by vertex indices: (0 4 8 0), (3 7 11 7), (0 1 5 4), (2 3 7 6), and (0 1 2 3). These faces define the borders exposed to the outdoor environment. Standard walls were used to group the internal faces between regions and other borders where the thermal insulation conditions are applied. On being the vertices of the specific faces: (8 9 13 12); (9 10 14 13); (10 11 15 14); (4 5 9 8); (5 6 10 9); (6 7 11 10) and (12 13 14 15), these faces represent internal walls and borders not exposed to the environment. Walls in zeroGradient set the boundary conditions for the Temperature (0/*T files), indicating that there is no normal heat flow to the walls or atmosphere in the outer region of the fixedValue air. As such, the temperature at the atmospheric boundary (outside air) was kept constant. The initial conditions for the outdoor temperature (0/*T files) were kept constant in the internalField across all regions, in accordance with the research design. The chipboard used has a thermal conductivity of 0.1 W/m·K (manufacturer's data), twice that of the pressed Ichu (0.05 W/m·K), suggesting it allows faster heat transfer. The density and specific heat are the same for both materials, which implies that the amount of energy required to change their temperatures per unit mass is the same. Air has a thermal conductivity (0.026 W/m·K) that is significantly lower than that of solids, which act as insulators by comparison (Atahuachi Layme & Carcausto Quispesayhua, 2018; Cárdenas Cristóbal & Espinoza Ramírez, 2024; Mendoza et al., 2021). The thermo-physical properties were determined according to the constant/*Thermophysical Properties and are shown in Table 1.

Next, the scenario prediction was made, and the data were processed using the free software OpenFOAM v12 for Windows and Salome Version 9.10.0, after being plotted in AutoCAD V25. Thermal comfort was calculated using a standard implementation of the ISO 7730 predicted mean

	Air	Ichu	Chipboard
Density (ρ) kg/m ³	1.225	250	250
Conductivity W/m·K	0.026	0.05	0.10
Specific heat (Cp) J/kg.K	1000	1200	1200

Table 1. Thermo-physical properties of the eco-friendly house's materials. Source: Manufacturer data; Atahuachi Layme & Carcausto Quispesayhua (2018); Cárdenas Cristóbal & Espinoza Ramírez (2024).

$$\begin{aligned}
 PMV &= (0,303e^{-0,036M} + 0,028) \\
 &\quad * \{(M - W) - 3,05 * 10^{-3} * [5733 - 6,99(M - V) - p_a] - 0,42[(M - V) - 58,15] - 1,7 * 10^{-5} * M \\
 &\quad * (5867 - p_a) - 0,0014 * M * (34 - t_a) - 3,96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} * h_c * (t_{cl} \\
 &\quad - t_a)\} \\
 t_{cl} &= 35,7 - 0,028 * (M - V) - I_{cl}\{3,96 * 10^{-8} * f_{cl}[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a)\} \\
 h_{cl} &= \begin{cases} 2,38 * |t_{cl} - t_a|^{0,25} & \text{si } 2,38 * |t_{cl} - t_a|^{0,25} > 12,1\sqrt{v_{ar}} \\ 12,1 * \sqrt{v_{ar}} & \text{si } 2,38 * |t_{cl} - t_a|^{0,25} < 12,1\sqrt{v_{ar}} \end{cases} \\
 f_{cl} &= \begin{cases} 1,00 + 1,290 * l_{cl} & \text{si } l_{cl} \leq 0,078 \frac{m^2}{w} \\ 1,00 + 0,645 * l_{cl} & \text{si } l_{cl} > 0,078 \frac{m^2}{w} \end{cases} \quad (\text{Equation 1})
 \end{aligned}$$

vote (PMV) formula (Olesen & Parsons, 2002). PMV is the standard used to determine thermal comfort under ASHRAE standards, based on Fanger calculations (Equation 1).

Where: M is the metabolic rate (W/m²); W is the external Work (W/ m²); I_{cl} is the clothing insulation (Clo); f_{cl} is the clothing Surface Area Factor; t_a is the air temperature (°C); t_r is the mean radiant temperature (°C), v_{ar} is the air velocity relative to the body (m/s); p_a is the partial pressure of water vapor in the air (Gilani, Khan & Pao, 2015).

The small variations were in the indoor temperature and humidity results. The air velocity was kept constant at 0.1 m/s, with a clothing insulation (clo) of 1.0, corresponding to moderate winter clothing. The Average Radiant Temperature (T_{mr}) was the same as the indoor Temperature, and a Metabolic Activity Level (Met) of 1.0 for a pure sedentary lifestyle was used to reflect the accuracy of the experimentation under the discrete scale of Table 2, where the thermal comfort zones follow the methodology (Fanger, 1970) and ASHRAE standards in Mora & Bean (2018), as the thermal comfort values are divided into three classes based on the PMV (Roelofsen & Jansen, 2024)

The statistical analyses were processed in the Minitab version 20 educational license software, using the DOE Experimental Design and RSM Response Surface of Composed Central Design of 13 treatments (4 negative, 4 positive, and 5 axial

Comfort	PMV
Very cold	-3.0
Pretty cold	-2.0
Somewhat cold	-1.0
Neutral	0
Somewhat hot	+ 1.0
Pretty hot	+ 2.0
Very hot	+ 3.0
Class	PMV intervals
A	-0.2 < PMV < 0.2
B	-0.5 < PMV < 0.5
C	-0.7 < PMV < 0.7

Table 2. Discrete scale and predicted mean vote classes, PMV. Source: Mora & Bean (2018).

points) (Table 3), from which the contour plots, solid meshes, interactions, and optimization were obtained.

The optimal wall width was determined by minimizing the acceptable thermal comfort according to ISO 7730 (Ergonomics of the thermal environment) and by analytically assessing thermal comfort (Fanger, 1970; Olesen & Parsons, 2002) using the PMV. The interval considered comfortable for class C starts at -0.7, because it is only somewhat cold, and extends

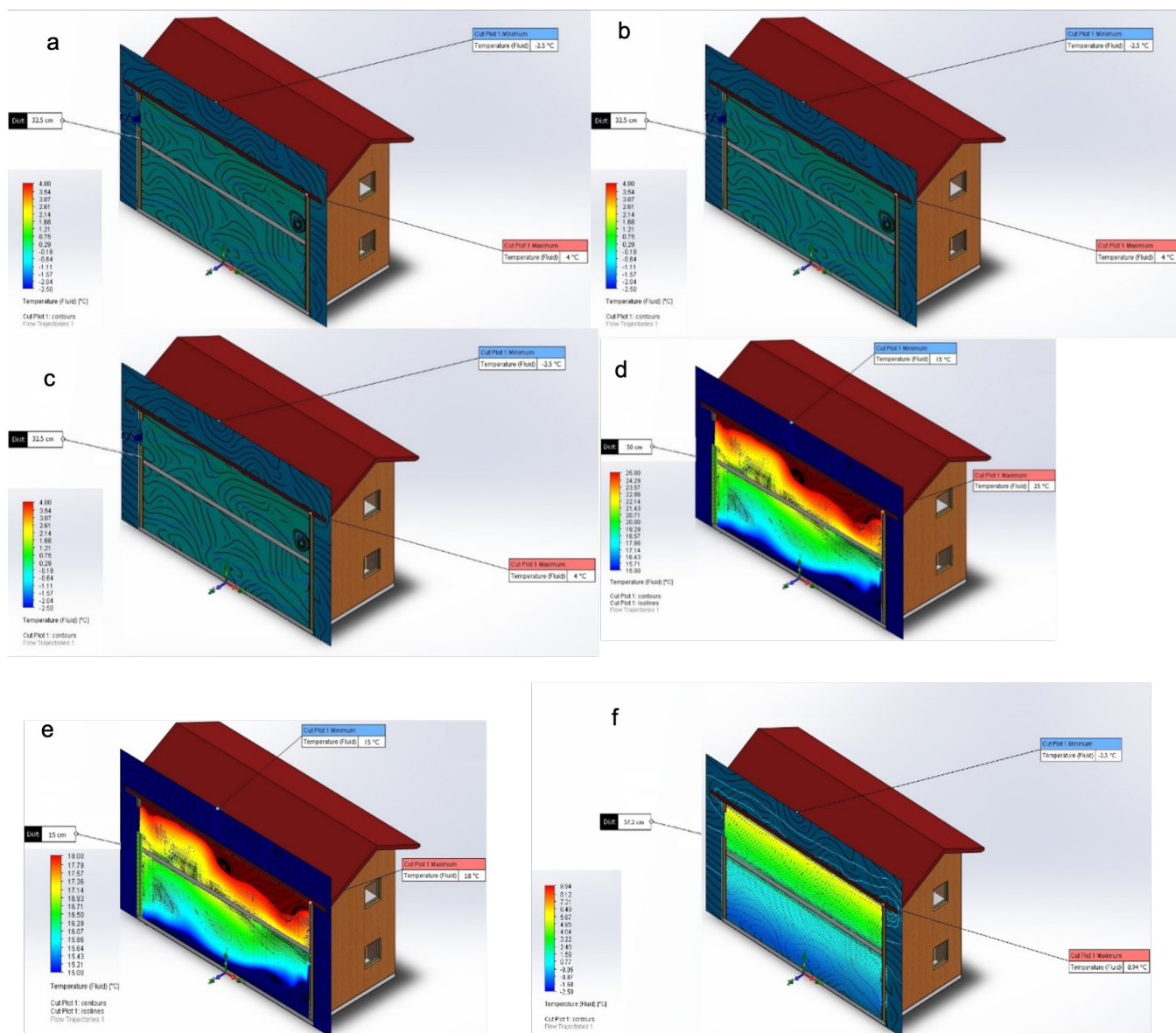


Figure 3. Comparison of the eco-friendly house's CFD simulations using the experimental optimization design, showing the wall thicknesses and outdoor and indoor temperature scales. Part 1. Source: Prepared by the authors.

up to +0.7; the best values are close to 0. Those of class A vary from -0.2 to +0.2, simulated at the extreme temperatures of -10 °C and -20 °C.

RESULTS

CFD SIMULATION

The thermal comfort behavior inside the eco-friendly house is shown graphically. Low temperatures of up to 4 °C are observed throughout the house in Figures 3a, 3b, and 3c when the outdoor temperature is -2.5 °C, and the wall thickness is 32.5 cm. This internal

temperature effect increases to 8.94 °C when the wall is 57.2 cm thick, and the wind temperature is higher on the upper floor than on the lower, with greater coldness on the lower floor (Figure 3f).

Outdoor temperatures of 22.24°C and wall thicknesses of 32.5 cm cause overheating inside, reaching up to 28.74°C on the second floor and a minimum of 22.24°C (Figure 4a). At this level, switching to lighter clothing is recommended. By reducing the wall thickness to 7.75 cm at sub-zero temperatures, as shown in Figure 4b, temperatures near 0°C are achieved. At temperatures below -20°C and wall thicknesses between 32.5 cm and 50 cm, thermal discomfort is observed in these cold spots inside. Figure 3c - Figure 3g.

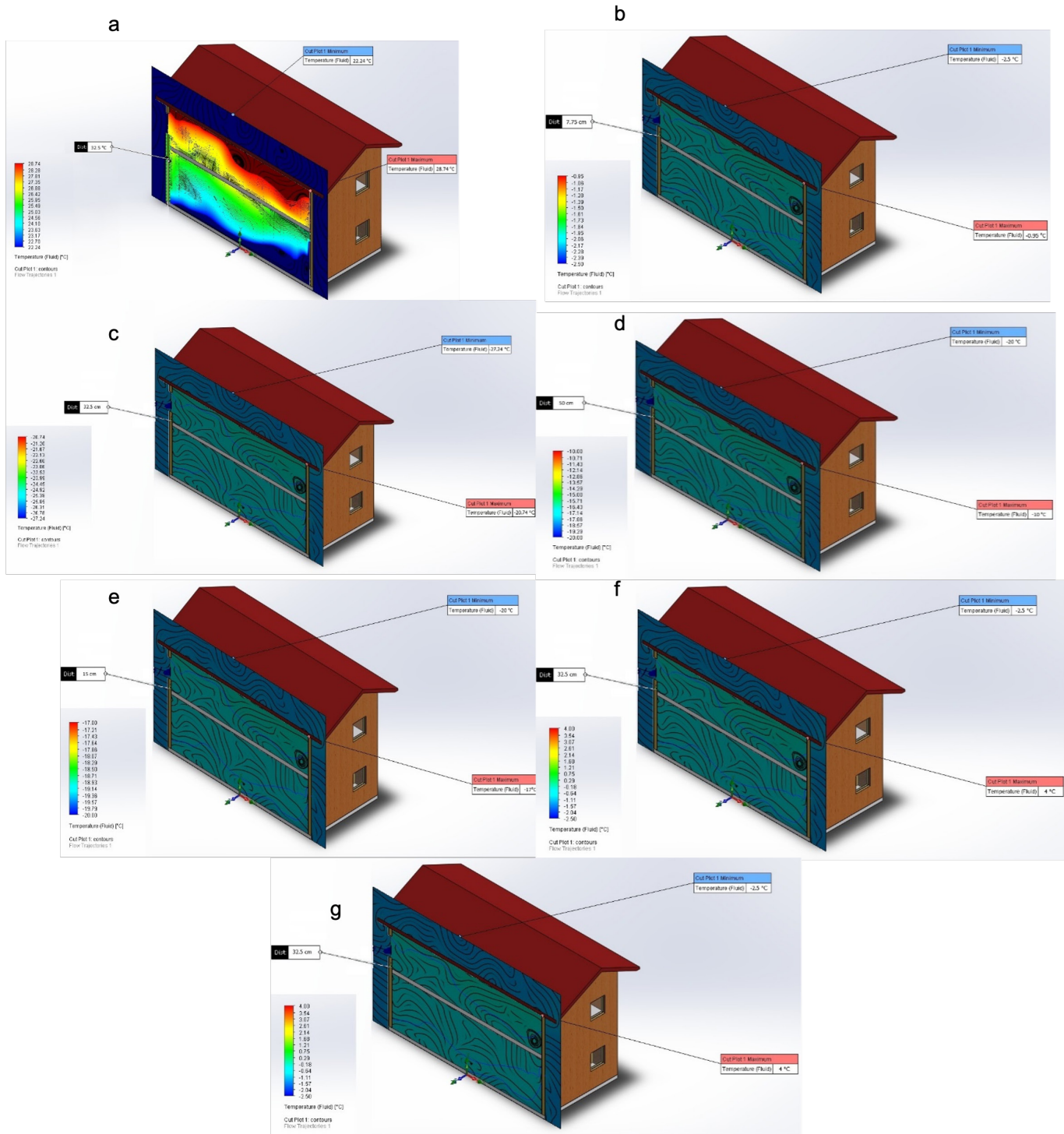


Figure 4. Comparison of the eco-friendly house's CFD simulation, based on the experimental optimization design, showing wall thicknesses and indoor and outdoor temperature scales. Part 2. Source: Prepared by the authors.

Wall thickness has a first-degree effect, and the temperature outside the eco-friendly house has a second-degree effect. This shows that both factors are highly significant ($\alpha = 0.05$) for thermal comfort inside the house, but with complex effects regarding outdoor temperature, with the PMV index varying counterintuitively at very cold outdoor temperatures (Figure 5a)

The contour diagram (Figure 5c) shows thermal comfort zones even at low temperatures ranging from 0°C to -20°C. This becomes possible by increasing the thickness of the wall containing the ichu. If PMV values between -0.7 and 0.7 are considered comfortable, it is possible to achieve comfort with wall thicknesses above 40 cm, and the ichu can even enhance thermal comfort in temperate climates up to an ambient temperature of 15°C.

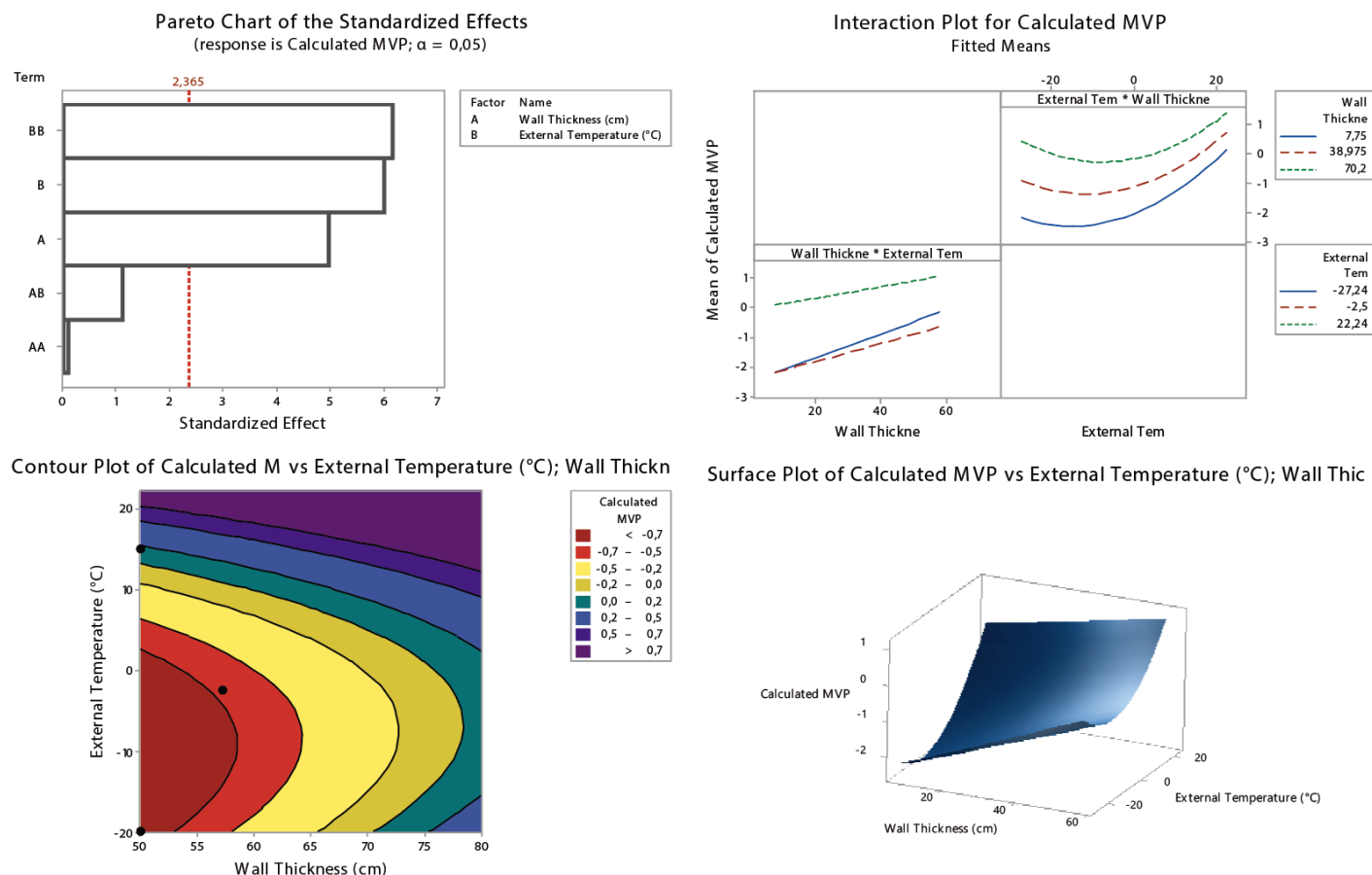


Figure 5. a) Pareto diagram identifies the standardized effects. b) Interaction of PMV means. c) Contour plot showing the spaces of thermal comfort and discomfort. d) 3D graph of thermal comfort in the eco-friendly house. Source: Prepared by the authors.

In Figure 5d, the 3-D response surface graph shows that higher temperatures and thicker wall thicknesses (optimization values) yield higher PMV values, which even exceed the thermal comfort ranges (classes A, B, and C). This value decreases with the wall thickness and when the temperature drops to extreme levels (-20°C). The thermal comfort range of class A is from -0.2 to 0.2, class B from -0.5 to 0.5, and class C from -0.7 to 0.7. It can be seen that thermal comfort can be achieved using PMV with wall thicknesses of 50, 60, and 65 cm for extreme temperatures from -10 °C to -20 °C (Zheng et al., 2021).

Specific calculations were conducted to determine the minimum wall thicknesses at -10 °C for PMV values of 0, -0.7, -0.5, and -0.2. The minimum thickness is 57.20 cm (Figure 6a – Figure 6d), and for temperatures of -20 °C, minimum thicknesses of 57, 53.07, 57.20, and 57.20 were obtained, respectively (Figure 6e – Figure 6h).

THERMAL COMFORT CALCULATION USING THE PREDICTED MEAN VOTE (PMV)

The model was subjected to thermal comfort assessment using PMV, following the experimental design, with wall thickness (cm) and external temperature (°C) as variables for the eco-friendly house. The other external parameters were kept constant. The results are shown in Table 3 as per the response surface design.

DISCUSSION

The wood chipboard's higher thermal conductivity (0.10 W/m·K) indicates that temperature changes propagate through it faster than through Ichu (0.05 W/m·K). The value obtained from the simulation is

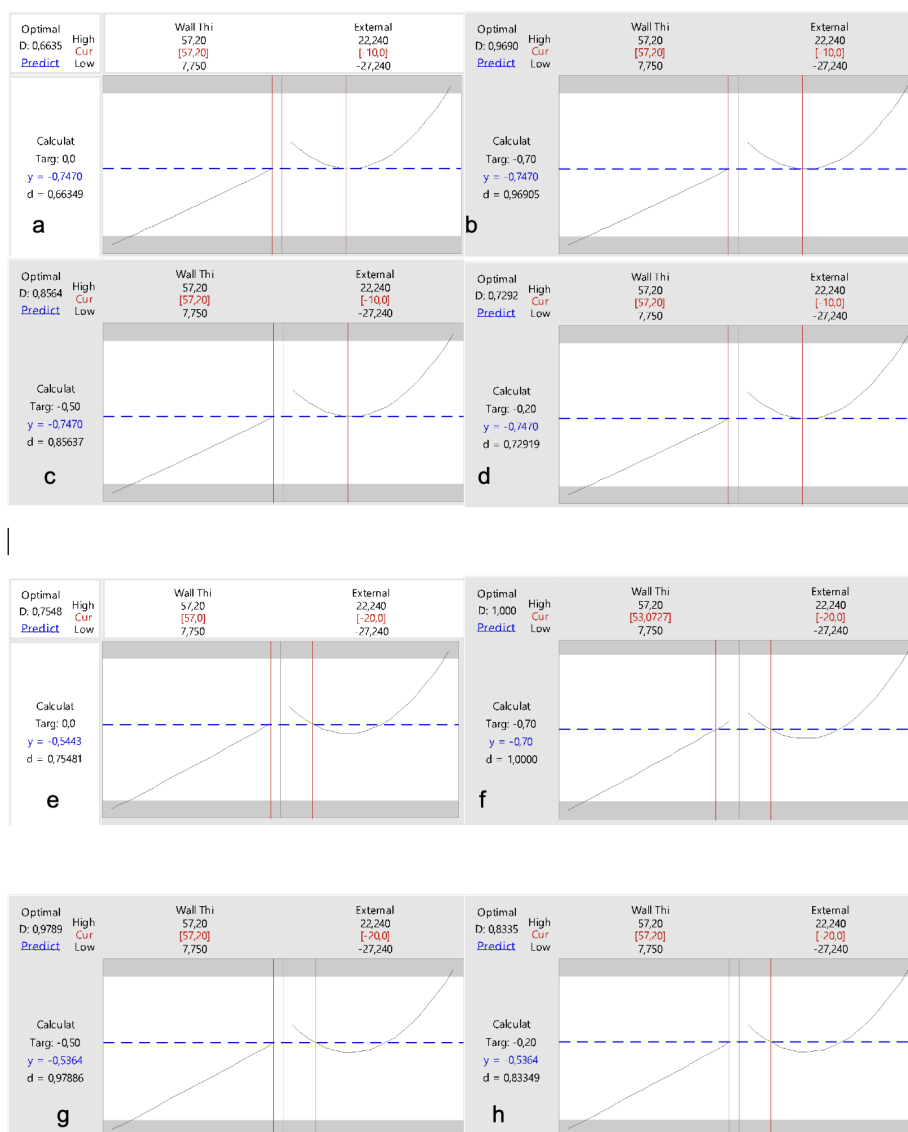


Figure 6. Optimization of wall thickness at extreme temperatures of -20 °C and -10 °C, with prediction and acceptable desirability. Source: Prepared by the authors.

Wall thickness (cm)	Outdoor temperature (°C)	Indoor temperature	PMV Calculation
32.5	-2.5	16	-1.29
32.5	-2.5	15.5	-1.42
32.5	-2.5	15	-1.57
50	15	20	0
15	15	17	-0.99
57.2	-2.5	18	-0.69
32.5	22.24	24	0.89
7.75	-2.5	14	-1.92
32.5	-27.24	16	-1.29
50	-20	18	-0.69
15	-20	13	-2.22
32.5	-2.5	16	-1.35
32.5	-2.5	15	-1.55

Note: The repetitions in Table 3 are the central points of the experimental design and allow measuring the model's variance and clearly reflect the system's sensitivity to thermal inertia. As the house can store heat, the internal temperature and PMV are not static; they exhibit slight fluctuations due to the flow of waste heat produced by the thermal cycle.

Table 3. Optimization design and thermal comfort calculation using the eco-friendly house's predicted mean vote (PMV). Source: Prepared by the authors.

consistent with the findings of Mendoza et al. (2021), who reported values ranging from 0.047 to 0.113 W/m·K. This emphasizes the model's fidelity. Ichu has insulating properties, with a thermal conductivity lower than that of screw wood (0.141 W/m·°C); this property supports the proposed structural model, and it is readily found in the Andean Highlands, where cold temperatures affect the inhabitants (Mendoza et al., 2021). The layout of the eco-friendly house evidences different thermal behaviors. In the house's roof, higher temperatures are recorded in all the simulations, presumably due to the use of tiles (thermal conductivity of 0.476 W/m·K), wood, and chipboard in the ceiling that naturally increase the temperature (Rat et al., 2023; Suleiman et al., 1999). It should also be recalled that hot air always rises through the "chimney effect", explained by the movement caused by the air pressure difference (0.1 m/s) that drives the less dense air upward (Suárez & Molina, 2015).

A main finding is a quadratic relationship between outdoor temperature and PMV. There is an optimal external temperature at which the minimum thermal comfort occurs for a given wall thickness. This nonlinearity is an empirical result arising from the complex interaction between heat-transfer mechanisms (conduction and natural convection within the house) and energy storage in the different components.

The thickness of the wall with ichu is higher than the experimental results of Molina-Fuertes, Horn-Mutschler & Gómez-León (2024), who used 0.4 m glass wool to achieve an indoor thermal amplitude of 17.1 °C, outdoor at 6.4 °C, and adobe walls with 0.40 m solid wood in the form of a shutter placed at night, which achieves values close to thermal comfort. It can be confirmed that using ichu inside the walls to preserve the house's internal heat longer would require slightly more space than other materials currently used. Several thermal comfort zones have been identified even at temperatures below -20°C by thickening the wall with ichu and sandwich-type chipboard; both materials have a relatively low thermal conductivity (0.05 W/m·K and 0.10 W/m·K, respectively). Increasing wall thickness increases Δx in the thermal resistance equation, thereby increasing the wall's thermal resistance and reducing the rate of heat flow from the warm inside to the cold outside (González-Domínguez, Monzón-Verona & García-Alonso, 2019). The indoor temperature remains stable and is affected less by the outdoor temperature at -20°C and -10°C when the wall thickness exceeds 57.20 cm, resulting in better PMV.

The recommended thickness of 57.20 cm satisfies the ISO 7730 standard, and optimal thermal comfort is

achieved with a PMV close to 0, with an acceptable class A range generally between -0.2 and +0.2 (Olesen & Parsons, 2002). The calculated wall width to achieve thermal comfort based on the PMV is consistent with the thermal resistance of the wood and the ichu in a sandwich-type arrangement and is economically sustainable (van Niekerk, 2020). So, it is confirmed that these optimized values are an economic inclusion for inhabitants of the cold highlands and extreme temperatures in light of the Sustainable Development Goals (United Nations, 2019).

The validation of the optimized thickness of 57.2 cm is performed by comparing the Total Thermal Resistance (R_t) with conventional materials. Ichu's conductivity ($k=0.05$ W/m·K) allows a proposed wall with $R_t=11.44$ m²·K/W, whereas a standard adobe wall ($k=0.80$ W/m·K) would require 9.15 m to achieve the same insulation (Piñas et al., 2020). The proposed width of the sandwich-type wall, although it appears thick by urban standards, is efficient and realistic in extreme cold in rural areas, eliminating the need for high-energy active heating systems.

CONCLUSIONS

The chipboard/ichu/chipboard sandwich-type wall is a highly effective technical solution for thermal insulation in extreme cold climates. Using Response Surface Methodology (RSM), it was determined that a critical thickness of 57.2 cm provides Class A thermal comfort in an eco-friendly house at an outdoor temperature of -20 °C.

Wall thickness has a first-degree relationship with PMV, whereas external temperature has a quadratic effect, indicating complex interactions in achieving thermal comfort. Therefore, the loss of comfort increases nonlinearly due to the extreme decrease in outdoor temperature, underscoring the need for insulation thicknesses greater than conventionally needed in high Andean areas to counteract this physical phenomenon.

The computational fluid dynamics confirms thermal stratification in two-floor houses. The air displaced by the internal pressure difference is concentrated on the second floor, suggesting that the architectural design should prioritize sleeping areas on upper floors to take advantage of the heat generated by the sandwich system.

CONTRIBUTION OF AUTHORS CRediT:

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GLOSSARY OF TERMS AND ACRONYMS

CFD: Computational Fluid Dynamics. This is a discipline that uses algorithms and numerical methods to solve cases of fluid and heat transfer.

Thermal conductivity (k): The property to conduct heat; its units are W/mK

Spatial discretization: Division of the continuous domain into a finite number of cells.

Euler Scheme: An implicit first-order numerical method for the discretization of temporal derivatives.

Gauss Linear: Second-order discretization based on the Gauss divergence theorem.

Thermal inertia: The ability to maintain the energy received and release it progressively.

Hexahedral Mesh: Mesh composed of six-sided elements (cubes or prisms)

OpenFOAM: Open-source software for solving thermal and fluid simulation problems.

PMV: Predicted mean vote. It is an index that predicts the thermal sensation based on the mean of the votes.

PPD: Predicted percentage of dissatisfied. An index that counts thermally uncomfortable people.

RSM: Response Surface Methodology. Statistical and mathematical techniques for modeling and analyzing responses influenced by variables of interest.

BIBLIOGRAPHIC REFERENCES

Atahuachi Layme, G. M., & Carcausto Quispe Sayhua, Y. N. (2018). *Aislante termoacústico a base de Stipa Ichu para atenuar el ruido y cambios drásticos de temperatura en viviendas de sectores en expansión urbana de la ciudad de Puno*. [Tesis de maestría, Universidad Nacional del Altiplano]. Repositorio Institucional - UNAP. <https://repositorio.unap.edu.pe/handle/20.500.14082/11138>

Cárdenas Cristóbal, J. M., & Espinoza Ramírez, K. (2024). Utilización de unidades termo-modulares de vivienda para combatir el frío extremo con materiales oriundos de Tayabamba - La Libertad - 2021 [Tesis de pregrado, Universidad Nacional del Santa]. Repositorio Institucional - UNS. https://alicia.concytec.gob.pe/vufind/Record/UNSR_09f576f8c5882bcc0a5e467258693592/Description#details

Charca, S., Noel, J., Andia, D., Flores, J., Guzman, A., Renteros, C., & Tumialan, J. (2015). Assessment of Ichu fibers as non-expensive thermal insulation system for the Andean regions. *Energy and Buildings*, 108, 55–60. <https://doi.org/10.1016/j.enbuild.2015.08.053>

Fanger, P. O. (1970). *Thermal comfort: analysis and applications in environmental engineering*. Danish Technical Press.

Frías, M., Caneda-Martínez, L., Sánchez de Rojas, M. I., Tenazoa, C., & Flores, E. (2020). Scientific and technical studies on eco-efficient binary cements produced with thermally activated ichu grass: Behaviour and properties. *Cement and Concrete Composites*, 111, 103613. <https://doi.org/10.1016/j.cemconcomp.2020.103613>

Gilani, S. I. U. H., Khan, M. H., & Pao, W. (2015). Thermal Comfort Analysis of PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings. *Energy Procedia*, 75, 1373–1379. <https://doi.org/10.1016/J.EGYPRO.2015.07.218>

González-Domínguez, P. I., Monzón-Verona, J. M., & García-Alonso, S. (2019). New Thermal-Conductivity Constitutive Matrix in Fourier's Law for Heat Transfer Using the Cell Method. *Applied Sciences*, 9(21), 4521. <https://doi.org/10.3390/APP9214521>

Hills, J. (2012). *Getting the measure of fuel poverty: final report of the Fuel Poverty Review*. CASE report 72. <https://sticerd.lse.ac.uk/dps/case/cr/casereport72.pdf>

Hodson, T. O. (2022). Root-mean-square error (RMSE) or mean absolute error (MAE): when to use them or not. *Geoscientific Model Development*, 15(14), 5481–5487. <https://doi.org/10.5194/GMD-15-5481-2022>

- Marchante González, G., & González Santos, A. I. (2020). Evaluación del confort y disconfort térmico. *Ingeniería Electrónica, Automática y Comunicaciones*, 41(3), 21–40. <https://dialnet.unirioja.es/servlet/articulo?codigo=9513886>
- Mendoza, M. A., Piñas Moya, M. J., Horn Mutschler, M. J., & Gómez León, M. M. M. (2021). Conductividad térmica de compuestos tipo sándwich usados en la industria de la construcción. *TECNIA*, 31(1), 42–50. <https://doi.org/10.21754/tecnia.v21i1.1198>
- Molina-Fuertes, J. O., Horn-Mutschler, M. J., & Gómez-León, M. M. (2024). Evaluación del comportamiento térmico de un sistema constructivo de pared en zona altoandina utilizando un módulo experimental. *Tecnia*, 34(2), 53–61. <https://doi.org/10.21754/TECNIA.V34I2.2170>
- Mora, R., & Bean, R. (2018). Thermal Comfort: Designing for People. *Ashrae Journal*, (02), 40-46. <https://commons.bcit.ca/besys/files/2018/08/Thermal-Comfort-Design-for-People.pdf>
- Moreno-Casas, P. A., Scott, F., Delpiano, J., & Vergara-Fernández, A. (2020). Computational tomography and CFD simulation of a bio filter treating a toluene, formaldehyde and benzo [a] pyrene vapor mixture. *Chemosphere*, 240, 124924. <https://doi.org/10.1016/j.chemosphere.2019.124924>
- Naciones Unidas. (2019). *Informe de Los Objetivos Del Desarrollo Sostenible 2019*. Naciones Unidas Nueva York https://ods.org.mx/docs/doctos/SDG_Report2019_es.pdf
- Olesen, B. W., & Parsons, K. C. (2002). Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy and Buildings*, 34(6), 537–548. [https://doi.org/10.1016/S0378-7788\(02\)00004-X](https://doi.org/10.1016/S0378-7788(02)00004-X)
- Ortiz Caicedo, P. L., Gonzales Vega, A. A., Montaña Roldan, V. L., Chica Tambaco, A. J., & Álava Vélez, C. E. (2023). Eficiencia de sistemas de aislamiento térmico. *Ibero-American Journal of Engineering & Technology Studies*, 3(2), 43–50. <https://doi.org/10.56183/IBEROTECS.V3I2.631>
- Piñas, J. M., Lira, L., Horn, M., Solis, J. L., & Gómez, M. M. (2020). Influence of Stipa ichu on the thermal and mechanical properties of adobe as a biocomposite material. *Journal of Physics: Conference Series*, 1433(1), 012003. <https://doi.org/10.1088/1742-6596/1433/1/012003>
- Presidente de la Comisión Organizadora de la UNAAT. (24 de enero de 2017). *Año del Buen Servicio al Ciudadano. RESOLUCIÓN DE PRESIDENCIA N° 007-2017-CO-P-UNAAT*. Universidad Nacional Autónoma Altoandina de Terma [<https://cdn.www.gob.pe/uploads/document/file/2178617/RESOLUCI%C3%93N%20DE%20PRESIDENCIA%20N%C2%B0%20007-2017-CO-P-UNAAT.pdf>]
- Rat, E., Martínez-Martínez, S., Sánchez-Garrido, J. A., Pérez-Villarejo, L., Garzón, E., & Sánchez-Soto, P. J. (2023). Characterization, thermal and ceramic properties of clays from Alhabia (Almería, Spain). *Ceramics International*, 49(9), 14814–14825. <https://doi.org/10.1016/J.CERAMINT.2022.05.328>
- Roelofsen, P., & Jansen, K. (2024). Modification in the (NEN-) EN-ISO 7730 Model, with Regard of the Thermal Indoor Climate Assessment in Dutch Offices. *Journal of Building Design and Environment*, 2(2), 35033. <https://doi.org/10.37155/2811-0730-0302-15>
- Suárez, C., & Molina, J. L. (2015). Análisis del efecto chimenea en fachadas ventiladas opacas mediante correlaciones del flujo másico inducido. Aplicación para el dimensionado de anchos de cámara. *Informes de la Construcción*, 67(538), e087. <https://doi.org/10.3989/IC.13.155>
- Suleiman, B. M., Larfeldt, J., Leckner, B., & Gustavsson, M. (1999). Thermal conductivity and diffusivity of wood. *Wood Science and Technology*, 33(6), 465–473. <https://doi.org/10.1007/S002260050130>
- Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(10–11), 1749–1761. <https://doi.org/10.1016/J.JWEIA.2008.02.058>
- van Niekerk, A. J. (2020). Inclusive Economic Sustainability: SDGs and Global Inequality. *Sustainability* 12(13), 5427. <https://doi.org/10.3390/SU12135427>
- Zheng, Z., Zhang, Y., Mao, Y., Yang, Y., Fu, C., & Fang, Z. (2021). Analysis of SET* and PMV to evaluate thermal comfort in prefab construction site offices: Case study in South China. *Case Studies in Thermal Engineering*, 26, 101137. <https://doi.org/10.1016/J.CSITE.2021.101137>

