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Adaptative comfort modeling for a typical non-centrifugal cane sugar processing facility

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Abstract
The production of non-centrifuged cane sugar in Colombia takes place in post-harvest facilities that generate significant heat and steam resulting from the evaporation of cane juices during the process. This study aimed to improve the comfort conditions of a facility of this type in the municipality of Pacho, Cundinamarca, Colombia, through bioclimatic simulation, where the enclosure on the walls and the lantern window were modified. The evaluation of adaptative thermal comfort revealed that configurations with open perimeter and lantern window demonstrated the best bioclimatic behavior. This is attributed to the increased ventilation area and chimney effect, which optimizes the transfer of heat and mass. Likewise, it was observed that there is a generalized behavior of thermal discomfort for workers in the thermal zone of the oven, due to the high emissions of heat and steam in this specific area.

Keywords: thermal stress; computer simulation; natural ventilation; thermal load; panela.

Modelamiento de confort adaptativo para un trapiche panelero

Resumen
La producción de azúcar de caña no centrifugada, en Colombia se realiza en instalaciones de poscosecha que generan alta cantidad de calor y vapor, producto de la evaporación de los jugos de caña del proceso. Este estudio tuvo como objetivo mejorar las condiciones de confort de una instalación de este tipo en el municipio de Pacho, Cundinamarca, Colombia, a través de simulación bioclimática, donde se modificó el cerramiento en las paredes y en la ventana cenital. Se evalúo el confort térmico adaptativo, donde el mejor comportamiento bioclimático se presentó en las configuraciones con perímetro abierto y ventana cenital, esto debido a que una mayor área de ventilación y efecto chimenea optimizan la transferencia de calor y masa; así mismo, se observó que hay un comportamiento generalizado de incomodidad térmica para los trabajadores en la zona térmica hornilla, debido a las altas emisiones de calor y vapor en esta zona.

Palabras clave: estrés térmico; simulación computacional; ventilación natural; carga térmica; panela.

1 Introduction

The production of non-centrifuged cane sugar (NCS), as defined by FAO [1] and referred to as “panela” in Colombia [2], involves the extraction, purification and concentration of sugar cane juices [3]. This traditional agroindustry holds significant importance in the rural sector of Colombia [4].

Colombia is the second world producer of NCS with 14.9% after India [5,6], and has the highest per capita consumption of panela, with 24 kg/person/year [7]. According to [8] more than 350,000 families participate in cultivation.

The processing and preparation of NCS in Colombia primarily occurs in traditional buildings called trapiches [9], and industrially in NCS honey plants. This activity is carried out one or two days every two or three weeks, when there is enough cane to process. As a result, most of the time workers work in the crops, and adapt better to external conditions than to the environment inside of the agroindustrial facilities.

Workers in this agroindustry generally undertake physically demanding tasks in conditions characterized by high relative humidity (often exceeding 80%), and elevated temperatures inside [10] (Fig. 1). Such working conditions can affect the health and performance of operators [11,12].

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a) b)

Figure 1. Exposure of workers to high humidity and temperature conditions in the Pacho Panela installation, a) RGB image, b) thermal image.
Source: Own elaboration

Industrial and agroindustrial workers are at risk of heat stress-related illnesses due to equipment emitting thermal radiation such as ovens and evaporators within facilities [13], psychological effects, reduced productivity, and increased incident rate [14–16].

In order to mitigate this type of adverse situations, bioclimatic architecture offers solutions focusing on suitable environmental conditions for occupants [17], emphasizing parameters of comfort, energy savings and environmental protection [18]. One of the most used bioclimatic and energy simulation tools is the free EnergyPlus™ software [19-21].

Comfort is defined as the mental condition expressing satisfaction with the environment [22], Thermal comfort is influenced by physical parameters such as dry bulb temperature, relative humidity, Average Radiant Temperature, and Air Velocity, and physiological and behavioral factors [23,24]. These factors can affect health, work productivity, and learning ability [25,26].

The adaptive comfort model is based on the principle that people tend to adapt physiologically and behaviorally to restore comfort if a change causes thermal discomfort [27,28]. According to [29] adaptive models show high potential for application in latitudes near the equator; Furthermore, the percentage of hours in which it is possible to use natural ventilation in regions close to the equator is between 50 and 90% of the hours of the year, unlike other regions where the use of natural ventilation is limited by season changes.

The adaptive thermal comfort model included in the ASHRAE 55 standard emerged as a method for buildings with natural ventilation [30,31]. Two ranges are established according to the percentage of occupant acceptability, 80% corresponding to a temperature interval of ± 3.5°C for a typical application and 90% corresponding to a temperature interval of ± 2.5°C [32].

For a healthy work environment, the Colombian Ministry of Labor and Social Security recommends an air temperature between 14°C and 25°C, with relative humidity between 30% and 70% [33].

Currently, no reported studies have evaluated adaptive thermal comfort in agroindustrial plants for the preparation of NCS. Therefore, this study aimed to assess adaptive thermal comfort for workers in a traditional NCS production facility through computational simulation. It also seeks to evaluate different envelope configurations to improve the bioclimatic environment for workers.

2 Material and methods

This study was carried out at the NSC PachoPanela post-harvest facility situated in the municipality of Pacho, Cundinamarca, Colombia (N05°10'59"; W074°09'31", 1858 masl). The average temperature in this region is 20°C [34] and the monthly production of NSC ranges between 1 and 1.5 tons.

The simulation and analysis were conducted throughout the entire year, using an EPW (Energy Plus Weather) climate file. This approach aimed to observe the behavior within the facility over time, considering the daily climatic variations during activities such as grinding, evaporation of juices in the oven and other processes. The different activities and thermal zones inside the facility are show in Table 1.

The geometry of the installation was created using the SketchUp® program, and the Open Studio plugin (Fig. 2), which generated idf type files. The dimensions of this building are 20.30 m wide x 23.50 m long, with an average height of 4.10 m for the cane thermal zones, transit area, boiler, and molding. The oven thermal zone has a height of 6.50 m, and the roof is gabled in galvanized sheet with a slope of 35%.

Table 1.
Activities carried out at the facility during the preparation of NCS.

Thermal zone	Activity	People	Work hours
Cane area	Collection of sugar cane bagasse	1	24
	Grinding and extraction of cane juice	1	24
	Cane grinding	1	24
Transit area	Preparation of work - Intermittent traffic of workers during the work day	1	24
Furnace area	Oven management	1	13
	Removal of floating material from the juice.	1	13
	Evaporation of cane juices	1	13
Boiler area	Boiler feed	1	13
Molding	Molding and packaging	2	13

Source: Own elaboration

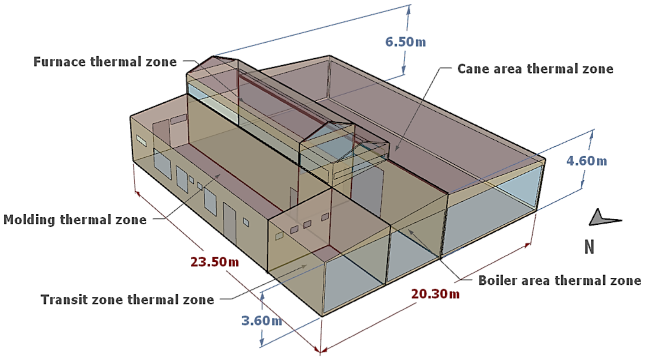


Figure 2. Geometry and thermal zones inside the facility.
Source: Own elaboration

Table 2.
Thermal properties of materials.

Material	λ	P	C
	W m^{-1} °K^{-1}	kg m^{-3}	kJ kg^{-1} °K^{-1}
Brick	1.05	1800	1.00
Wall ceramics	1.05	2000	0.92
Floor ceramics	1.05	2000	0.92
Galvanised steel	55	7800	0.42
Fibercement	0.65	1600	0.84
Clay	0.90	1500	0.92
Wood	0.15	600	1.34
Concrete	1.75	2200	1.00
Mortar	1.15	2000	1.00

λ: Thermal conductivity, ρ: density, C: Specific heat.
Source: Obtained from NBR-15220, (2005) [37] and LabEEE, (2015) [38].

Table 3.
Equipments power and metabolic rates for activities.

Thermal zone	Area	Lightning	Mill motor	Oven	Metabolic Rate
	m^2	W m^{-2}	W	W	W
Cane area	236	0.51	5965.6	-	568
Furnace	73	1.03	-	552706	520
Transit area	29	0.51	-	-	632
Molding	94	3.67	-	-	520
Boiler area	45	1.00	-	-	632

Source: Own elaboration

In each of the three critical work areas (furnace, cane area and molding), an Extech Rth10 humidity and temperature datalogger was installed, brand humidity and temperature dataloggers were installed, with a temperature range of -40 to 70°C, precision of ± 1 °C, relative humidity scale: 0 to 100% RH, with a resolution of 0.1°C, 0.1 HR.

The facility has a gable roof with galvanized zinc tiles, structural masonry walls, and concrete floor. The thermal properties of the composite materials were calculated [35], utilizing the simplified layer method [36]. Table 2 show the thermal properties of the construction materials.

To establish boundary conditions, it is necessary to calculate the heat generated within the construction. This encompasses the heat produced by machines, cooking processes, lighting, and human metabolism.

Table 3 presents the power values for lights, machines, and equipment (boiler), along with the metabolic rates per body surface area of the workers. It is noteworthy that a height of 1.6m^2 was considered [39].

The internal environment of the facility was simulated throughout the year considering various configurations for openings in the perimeter walls and open or closed lantern windows. This aimed to assess the impact of ventilation area variations within the facility. Considering that the installation's roof is currently made of zinc tile, the model with this roof and characteristics served as the control treatment (T1: installation without perimeter enclosure - open overhead window - zinc tile). The modeled treatments are outlined in Table 4 and Fig. 3.

Table 4.
Modeled treatments.

Treatments	Perimeter Enclosure			Lantern Window	
	Open	Solid Brick	Perforated Brick	Open	Closed
T1	X			X	
T2	X				X
T3		X		X	
T4			X	X	

Source: Own elaboration

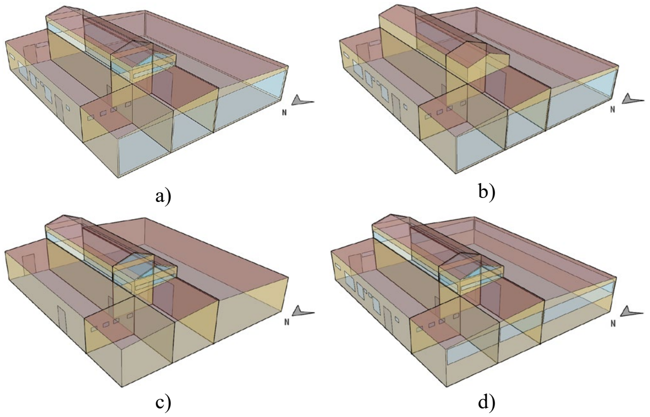

a) b) c) d)

Figure 3. Simulated treatments, a) T1; b) T2 c) T3; d) T14.
Source: Own elaboration

Table 5.
Coefficient A values as a function of air speed.

V_a (m s^{-1})	< 0.2	0.2 - 0.6	0.6 - 1.0
A	0.5	0.6	0.7

Source: Obtained from ASHRAE Standard 55, (2017) [27].

For this study, the adaptive comfort model proposed by [27], using the eq. (1) to find the value of the operative temperature (T_o).

$$T_o = A \cdot T_a + (1 - A) \cdot MRT \quad (1)$$

Where T_o: operative temperature (°C), T_a: average temperature of the previous month or of the season (°C), A: coefficient as a function of air speed (Table 5), MRT: mean radiant temperature (°C).

The MRT is determined using eq. (2) [39], with the black globe temperature (T_g) and dry bulb temperature (T_{db}).

$$MRT = \sqrt[4]{(T_g + 273)^4 + 0.4 \cdot 10^8 \cdot \sqrt[4]{|T_g - T_{db}|} \cdot (T_g - T_{db})} - 273 \quad (2)$$

Eq. (3) [40] allows us to estimate the black globe temperature from the dry bulb temperature.

$$T_g = -0.9387 + 0.8562 \cdot T_{db} + 0.0162 \cdot {T_{db}}^2 \quad (3)$$

Operating temperature includes MRT, which in this case helps to size the radiant thermal effect of the oven and the ceiling.

The operating temperature represents the climatic conditions to which occupants are relatively adapted and is graphically depicted as the neutral line [27]. Two levels of thermal comfort are established based on the occupant's percentage of acceptability. A comfort band is specified for 80% and 90% acceptability range [41] to operationalize an adaptive equation. Finally, results of the simulations carried out for each of the four treatments were compared.

The average daily operating temperature for each of the five thermal zones was considered as a variable (T_{oad}). The T_{oad} results were compared with the T_o graphically equivalent to the neutral line, along with the acceptability range of 80% and 90%, for the four treatments.

The agreement between the measured field values and those described by the EnergyPlus™ model (with Treatment 1) was evaluated using the normal mean square error (NMSE) calculated by eq. 4, recommended by the ASTM for the evaluation of indoor air quality models [42].

$$NMSE = \frac{1}{n}\sum_{i=1}^{n}\frac{(Y_{pi} - Y_{mi})^2}{Y_{pi}Y_{mi}} \tag{4}$$

Where $NMSE$: normal mean square error, Y_{pi}: predicted value, Y_{mi}: measured value, n: data number.

A total 151 temperature and relative humidity data were used for the furnace thermal zone, 278 for the cane thermal zone, and 145 data for the Molding thermal zone. The varying data numbers are different in each thermal zone because the activities have different time durations. Values with an NMSE less than 0.25 are accepted as good indicators of agreement. As this value approaches zero, the agreement between the measured and predicted values is greater [42].

Furthermore, a statistical analysis of means was carried out using the Tukey test ($P < 0.05$), to assess if there is a statistical difference between the different treatments or envelope configurations.

3 Results and discussion

Table 6 presents the comparison and validation result through NMSE between the data obtained from the computational model and the experimental data of the control treatment (T1), for the variables temperature and relative humidity. NMSE values < 0.25 show good agreement between the model results and the real data, which means it can represent the actual bioclimatic conditions of the facility, and it is used to accurately predict the environmental behavior of the facility inside.

Table 6.
Comparison of experimental and simulated temperature and relative humidity data.

Thermal zone			Average	NMSE
Furnace	T (°C)	S	25.08 +/- 3.91	
		M	24.90 +/- 3.31	0.00754
	RH (%)	S	73.54 +/- 14.94	
		M	80.17 +/- 8.80	0.03398
Cane area	T (°C)	S	23.02 +/- 3.29	
		M	25.57 +/- 3.93	0.03606
	RH (%)	S	76.44 +/- 13.77	
		M	80.23 +/- 7.91	0.03398
Molding	T (°C)	S	24.74 +/- 2.84	
		M	25.82 +/- 2.97	0.01510
	RH (%)	S	77.60 +/-12.22	
		M	78.69 +/-8.29	0.04726

T: temperature, RH: relative humidity S: simulation, M: measurement.
Source: Own elaboration

Table 7.
Percentage of mean operating temperature data below the upper limit of acceptability 80%.

	T1	T2	T3	T4
Boiler area	87.4	88.5	57.8	85.2
Transit area	99.2	98.4	67.9	95.9
Furnace	0.0	0.0	0.0	0.0
Molding	92.9	90.4	89.3	90.2
Cane area	90.4	83.6	36.4	88.5

Source: Own elaboration

Table 7 shows the percentage of daily mean operating temperature points above and below the 80% upper limit of acceptability for the four treatments, obtained from the simulation.

Table 7 illustrates that a high percentage of data in the four treatments falls within the acceptability range for comfort in the thermal zones: boiler area, transit area, molding and cane area. Treatments with open perimeter exhibit better comfort conditions, while the closed perimeter of solid brick (T3) shows the least favorable performance. In the furnace area thermal zone for all treatments, data surpass the upper limit of acceptability of 80% [32], indicating thermal stress.

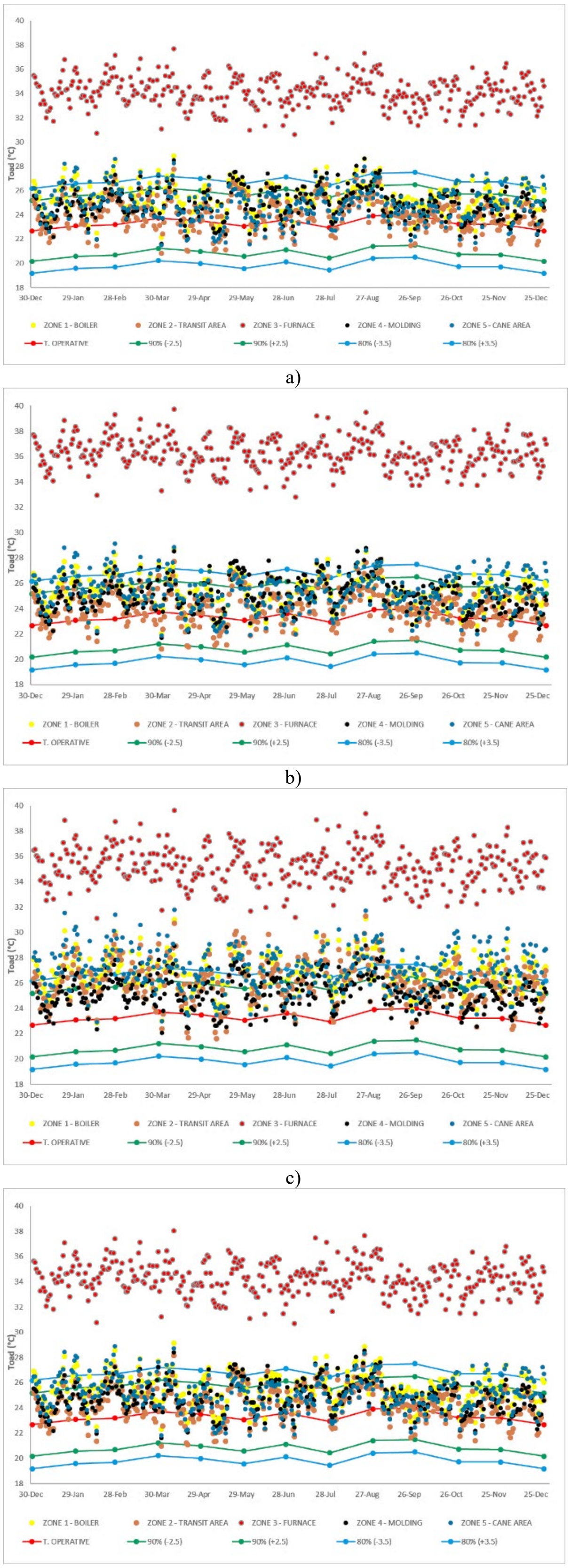
Fig. 4 graphically depicts the behavior of operating temperature over time for the 4 treatments, where most of the thermal zones offer comfort to the occupants for the majority of the time; with the treatment with open perimeter and lantern window (T1) providing the best conditions, followed by T2, attributed to a greater natural ventilation area. Special attention must be given to the hygrothermal conditions of workers in the furnace area. Additionally, there is a need to evaluate or improve the design of this area to mitigate heat stress.

As the T_o is contingent on MRT and the average air temperature within each thermal zone, when the perimeter walls are closed (T3), the transfer of energy and mass to the outside decreases. Consequently, the temperature and vapor concentration generated, arising from the evaporation of cane juices from the process, increase a lees favorable condition for the comfort of workers [24].

Similarly, for T4, the reduction in the percentage of days with T_{oad} within the comfort range for the four thermal zones (excluding the furnace thermal zone), results from reduced ventilation caused by the perforated brick enclosure. Despite this, it exhibits more favorable conditions compared to T3.

Table 8 shows means tests for T_{oad} in the five thermal zones across the four treatments, over a one-year period. The reference point considered the average of the values of the upper limit of acceptability (80%) of the comfort band, which is 26.80°C, across all twelve months of the year.

Across all treatments, the thermal zone of the oven exceeds the maximum limit of 26.80°C due to the presence of the oven and the hot vapors of the cane juice. Consequently, this zone does not provide comfortable conditions for workers. The highest value is observed in T2 with a value of 36.28°C. This could be attributed to the closed lantern window in this treatment, which reduces its natural ventilation area compared to T1, and the limited effectiveness of the chimney effect [43], essential for the transfer of energy and vapor mass.



a)

b)

c)

d)

Figure 4. T_{oad} in time compared with the values of T_o during the twelve months of the year in a) T1, b) T2, c) T3 y d) T4.
Source: Own elaboration

Table 8.
Tukey test for T_{oad} in the different treatments.

Zona térmica	n	T1	T2	T3	T4
Boiler area	365	25.30a +/- 1.23	25.22a +/- 1.23	26.67b +/- 1.43	25.44a +/- 1.23
Transit area	365	24.09c +/- 1.33	24.11c +/- 1.33	26.11bd +/- 1.68	24.32c +/- 1.36
Furnace	365	34.09e +/- 1.26	36.28f +/- 1.23	35.24g +/- 1.50	34.26e +/- 1.29
Molding	365	24.85ac +/- 1.28	25.04a +/- 1.31	25.19a +/- 1.27	24.82ac +/-1.27
Cane area	365	24.85ac +/- 1.39	25.29a +/- 1.42	27.07h +/- 1.65	25.07a +/- 1.38

Groups sharing the same letter indicate no significant statistical difference, as determined by the Tukey test with a value of P <0.001 and F = 3803.098.
Source: Own elaboration

To improve thermal comfort in the oven thermal zone, Studies have shown that reducing exposure duration is one way to protect employees against infrared radiation and high temperatures, wearing specialist clothes, such as aluminized garments, and appropriate eye protection, such as infrared-filtered glasses, can help prevent injuries or lessen their severity [44,45].

The values of T3 in general are higher, due to the perimeter enclosure. This treatment stands out as the only one where the cane area thermal zone falls outside average comfort conditions, and the boiler area hovers close to the upper limit of 80%.

As the natural ventilation area of the building decreases, the transfer of energy and vapor mass is reduced. Taking the above into account, heat and mass transfer is more effective in T1.

4 Conclusions

The architectural configuration that presented the best bioclimatic conditions in terms of operating temperature was observed in treatments with open perimeter walls. The best being the one that featuring open lantern window, confirming the importance of the natural ventilation area and the combination of dynamic and thermal ventilation for the rapid evacuation of heat and steam in such installations.

A consistent trend of thermal discomfort among workers in the furnace thermal zone was noted, attributed to the high emissions of heat and steam in the non-centrifuged cane sugar manufacturing process, which suggests that this space should be redesigned to provide a more suitable environment for operators working in this area.

Workers experienced comfortable conditions inside the facilities throughout the year, with the exception of the thermal zone of the furnace.

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