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Original Article

Assessment of thermal comfort in non-centrifugal cane sugar through WBGT index[1]

Avaliação do conforto térmico em instalação de processamento de rapadura por meio do índice IBUTG

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HIGHLIGHTS:

NCS agro-industrial facilities emit high amounts of heat and steam, which can create thermal stress for workers.
The WBGT index values suggest a ventilated environment to reduce negative impacts on workers' health and work performance.
Statistical treatments with open perimeter walls and lantern windows presented the best bioclimatic conditions for workers.

ABSTRACT: The production process of non-centrifuged cane sugar (NCS) involves a significant release of steam and heat due to the evaporation of cane juices in saucepans over a solid fuel oven. This results in a warm and moisture-saturated environment, which can be suffocating for workers. This study aimed to evaluate the bioclimatic behavior of an NCS processing facility, based on the wet bulb globe temperature (WBGT) index. In addition, solutions are suggested to mitigate possible adverse effects of heat stress. This evaluation utilized computational simulations to determine the thermal comfort perceived by the workers. The accuracy of simulations was verified against temperature and relative air humidity data collected from the facility. Bioclimatic simulations encompassed twelve treatments, involving modifications to the enclosure on the walls and lantern window, incorporating three types of roof material. The WBGT index was determined by considering the effects of the radiant heat generated by the oven and the natural ventilation area on the facility's temperature and relative air humidity. This helps to assess the comfort experienced by the workers. The thermal zone of the oven presented heat stress conditions; therefore, rest periods and mechanical ventilation were suggested when dissipating heat and steam through natural ventilation is not possible. For workers exposed to high temperatures and thermal radiation, the use of an aluminized apron and infrared goggles for eye protection was recommended.

Key words: heat stress, computational simulation, bioclimatic, passive conditioning strategies, agro-industry

RESUMO: O processo de produção de rapadura gera alta concentração de vapor e calor devido à evaporação do caldo da cana em panelas sobre forno a combustível sólido. Isso gera um ambiente quente e saturado de umidade que pode ser sufocante para os trabalhadores. Este estudo teve como objetivo avaliar as condições ambientais de uma instalação de processamento de rapadura, com base no Índice de Bulbo Úmido e Temperatura de Globo (IBUTG) e sugerir soluções para mitigar possíveis efeitos adversos do estresse térmico. Esta avaliação utilizou simulação computacional para determinar o conforto térmico dos trabalhadores. A simulação foi validada com dados de temperatura e umidade relativa do ar da instalação. As simulações bioclimáticas foram realizadas em doze tratamentos, modificando o fechamento nas paredes e lanternim, com três tipos de materiais de cobertura. Foi determinado o Índice IBUTG, considerando os efeitos do calor radiante gerado pelo forno, e pela área de ventilação natural sobre a temperatura e umidade relativa do ar no interior da instalação, e seu efeito no conforto dos trabalhadores. A zona térmica do forno apresentou condições de estresse térmico, portanto, foram sugeridos períodos de descanso e ventilação mecânica quando não for possível a evacuação do calor e vapor através da ventilação natural. O uso de avental aluminizado e óculos infravermelhos para proteção ocular foi recomendado para os trabalhadores expostos a altas temperaturas e radiação térmica.

Palavras-chave: estresse térmico, simulação computacional, bioclimática, estratégias de condicionamento passivo, agroindústria

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Introduction

Non-centrifugal cane sugar (NCS) is a natural sweetener obtained by concentrating sugarcane juice through its evaporation (Alarcón et al., 2021). In Colombia, this agro-industrial process is carried out in facilities called "trapiches" (MinSalud, 2006).

The workers in these facilities are exposed to environmental conditions with high temperatures (Vásquez et al., 2013) and humidity resulting from the cane juice evaporation process. In some cases, these buildings are not adequately designed to dissipate steam and heat. These conditions, combined with the physically demanding activities carried out within the facility, can lead to heat stress.

Heat stress can cause health problems, reduced performance and workability (Morris et al., 2020; Morrissey et al., 2021), and fertility problems (Aldahhan & Stanton, 2021). To address these concerns, the use of thermal protective clothing is suggested (Watson et al., 2021). Most sources of thermal radiation of industrial origin are harmful to eyesight (Mekjavic et al., 2021). In these situations, it is recommended to provide eye protection (Pouya et al., 2018).

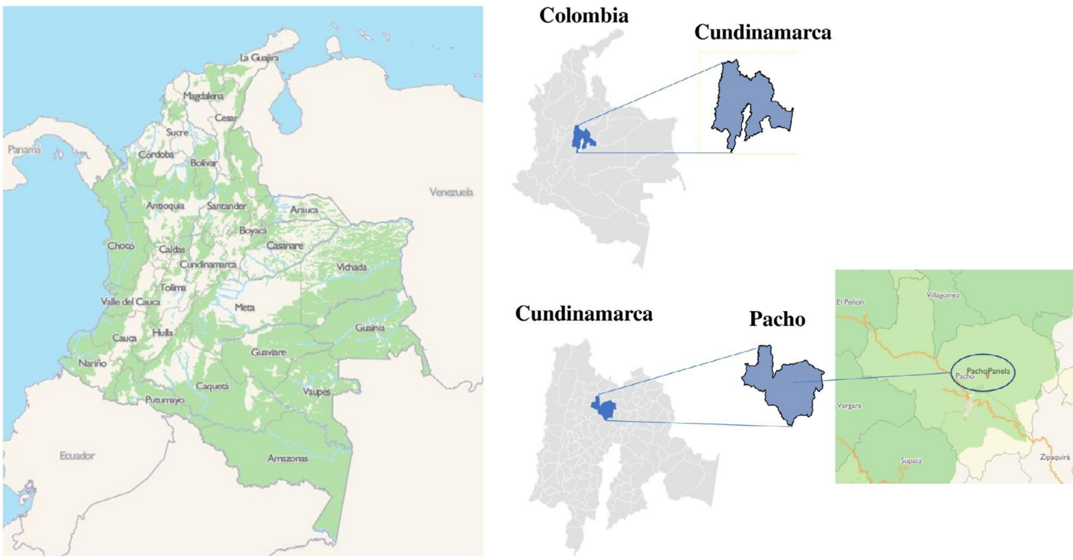
To evaluate the thermal comfort, the use of indices is required (Gungor et al., 2021). The wet-bulb globe temperature (WBGT) index considers the effects of humidity, dry bulb temperature, and black globe temperature. Different standards include the use of the WBGT in working environments prone to heat stress (ASHRAE, 2017; ISO, 2017). However, there are few studies in Colombia related to agro-industrial environments using this index (Guerra-García et al., 2022).

Bioclimatic simulation provides solutions focused on appropriate environmental conditions for occupants, emphasizing comfort, energy savings, and environmental preservation to mitigate these types of adverse situations (Calixto-Aguirre et al., 2021). This study aimed to evaluate the bioclimatic behavior of a NCS processing facility using the WBGT index and propose solutions to alleviate potential adverse effects of heat stress.

Material and Methods

This study was conducted in the Pacho Panela mill sugarcane, located in the municipality of Pacho, Cundinamarca (5° 10' 59" N and 74° 09' 31" W), at 1858 m above sea level (Source - taken and adapted from IGAC, 2022, Figure 1). The average temperature was 20 °C, while the average relative air humidity was 78% (IDEAM, 2021). The facility produces between 1 and 1.5 tons of NCS per month.

EnergyPlus™ (version 9.6) is an open-source bioclimatic simulation software (Saafi & Daouas, 2019). Simulations and analyses were carried out throughout the year to observe the hygrothermal behavior within the facility over time, considering the variation of daily environmental conditions during the grinding and processing of juices in the furnace. The different activities within the facility can be found in Table 1.



Source - Taken and adapted from IGAC (2022)

Figure 1. Geographical location of the municipality of Pacho, Cundinamarca, Colombia

Table 1. Activities for the production of non-centrifugal cane sugar (NCS) at the facility

Thermal Zone	Activity	Number of people	Duration (hours)
Cane area zone	Bagasse collection	1	24
	Cane stacking	1	24
	Cane grinding	1	24
Transit zone	Preparation of work - intermittent traffic of workers during the work day	1	24
Furnace zone	Furnace management	1	13
	Removal of floating material	1	13
	Juice density test	1	13
Boiler	Boiler fuel feed	1	13
Molding	Molding and packaging/Heat sealing	2	13 (0.5 hours 100 kg^{-1})

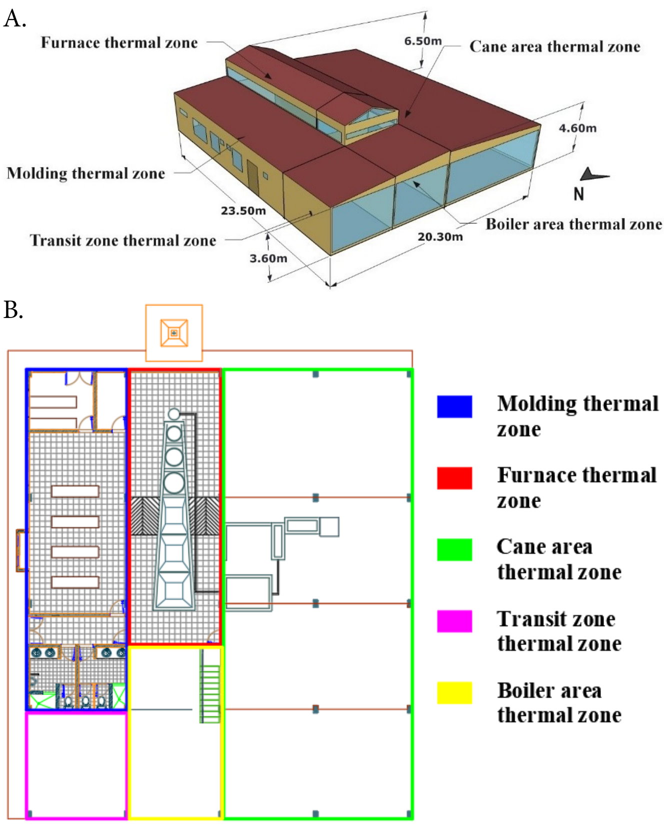
The facility is 20.3 m wide and 23.5 m long, with an average height of 4.1 m in the cane storage, milling, boiler, and molding areas, while the furnace area has a height of 6.5 m (Figure 2B).

In the three critical work areas, i.e., furnace, cane storage, and molding, EXTECH Rth10 brand humidity and temperature dataloggers were installed, with a temperature range of −40–70 °C, an accuracy of ± 1 °C, and a relative air humidity (RH) scale from 0 to 100% with a resolution of 0.1%. Temperature and RH data were collected every minute during three grinding sessions and two reference days. The sensors were located at an average hypothalamic height of 1.50 m above ground level. No sensors were installed in the worker transit areas. The surface temperature within the facility was recorded using a FLIR SYSTEMS T640 thermal camera, with a thermal sensitivity of 0.05 at 30 °C, a spectral response of 7.5 at 13 UM, an image frequency of 30 Hz, and a temperature range between −20 and 2,000 °C.

The facility's enclosure consists of coated masonry that is 0.15 m thick, stuccoed, and painted on the exterior. The gabled roof is made of galvanized sheet tiles, with a 35% slope. The cover structure is made of bamboo. The structure consists of 25 reinforced concrete columns measuring 0.40 × 0.25 m, with beams to confine walls and support the bamboo structure. The floor material is concrete.

The geometry was made in the SketchUp program (Figure 2A), while the Open Studio plugin was used to generate idf-type files. The facility was divided into five thermal zones: cane area, transit zone, boiler, furnace, and molding. These were each analyzed independently.

Results from the model in EnergyPlus™ 9.6 were validated by calculating the normal mean square error (NMSE) using



Source - DNP, 2017

Figure 2. Facility for the preparation of NCS (A) and the geometry and thermal zones of the architectural plant (B)

Eq. 1, as recommended by the American Society for Testing Materials (ASTM, 2019). For this purpose, temperature and RH data were compared in different zones; 151 data points were compared for the furnace thermal zone, 278 for the sugarcane area thermal zone, and 145 for the molding thermal zone. The number of data points (n) is different in each thermal zone because the activities have different schedules and durations. Values with a NMSE less than 0.25 are accepted as good indicators of agreement.

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

Where:

n - number of data points;
Y_{pi} - predicted value; and
Y_{mi} - measured value.

All openings in the facility allow air exchange between the interior and exterior through natural ventilation. Details such as location, area, and opening percentage can be found in Table 2.

For the thermal properties of the composite materials of the walls and roofs, the simplified layer method was used (ABNT - NBR, 2022). Table 3 shows the thermal properties of the construction materials.

To establish the boundary conditions, it is necessary to calculate the heat generated within the facility, considering various processes, including machinery operation, cooking processes, lighting, and human metabolism. A mass flow of 100 kg h^{-1} of steam was assumed, with an evaporation temperature of 110 °C for the juices, a latent heat of vaporization of 2,230 kJ kg^{-1}, and a furnace thermal efficiency of 40%.

Table 4 shows the power values for each thermal zone. To determine the values for the metabolic rates per unit surface

Table 2. Windows and openings

Orientation	Window or opening	Amount	Area m^2	Opening %
North (N)	Window	7	5	50
	Lantern window	1	14.3	100
South (S)	Opening	1	80.85	100
	Lantern window	2	8.7	100
East (E)	Opening	3	44.1	100
	Window	1	0.6	80
West (W)	Opening	5	72	100

Table 3. Thermal properties of materials

Material	λ $W\ m^{-1}\ °K^{-1}$	ρ $kg\ m^{-3}$	C $kJ\ kg^{-1}\ °K^{-1}$
Brick	1.05	1800	1.00
Wall ceramics	1.05	2000	0.92
Floor ceramics	1.05	2000	0.92
Galvanized Steel	55	7800	0.42
fiber cement	0.65	1600	0.84
Clay pottery	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; and C - Specific heat. Source - Adapted from ABNT - NBR (2022)

Table 4. Equipment power and metabolic rates

Thermal Zone	Area m²	Lighting power W	Mill motor power W	Furnace power W	Metabolic rate W
Cane area zone	236.04	0.51	5,965.6	-	568
Transit zone	72.84	1.03	-	552706	520
Furnace	29.23	0.51	-	-	632
Boiler	93.96	3.67	-	-	520
Molding	45.18	1.00	-	-	632

area of the body of the workers in each thermal zone, an area of 1.6 m² was assumed based on an adult person of short stature and thin build (Lamberts et al., 2014).

The modeled treatments are shown in Table 5 and Figure 3, with treatment T1 being the original geometry.

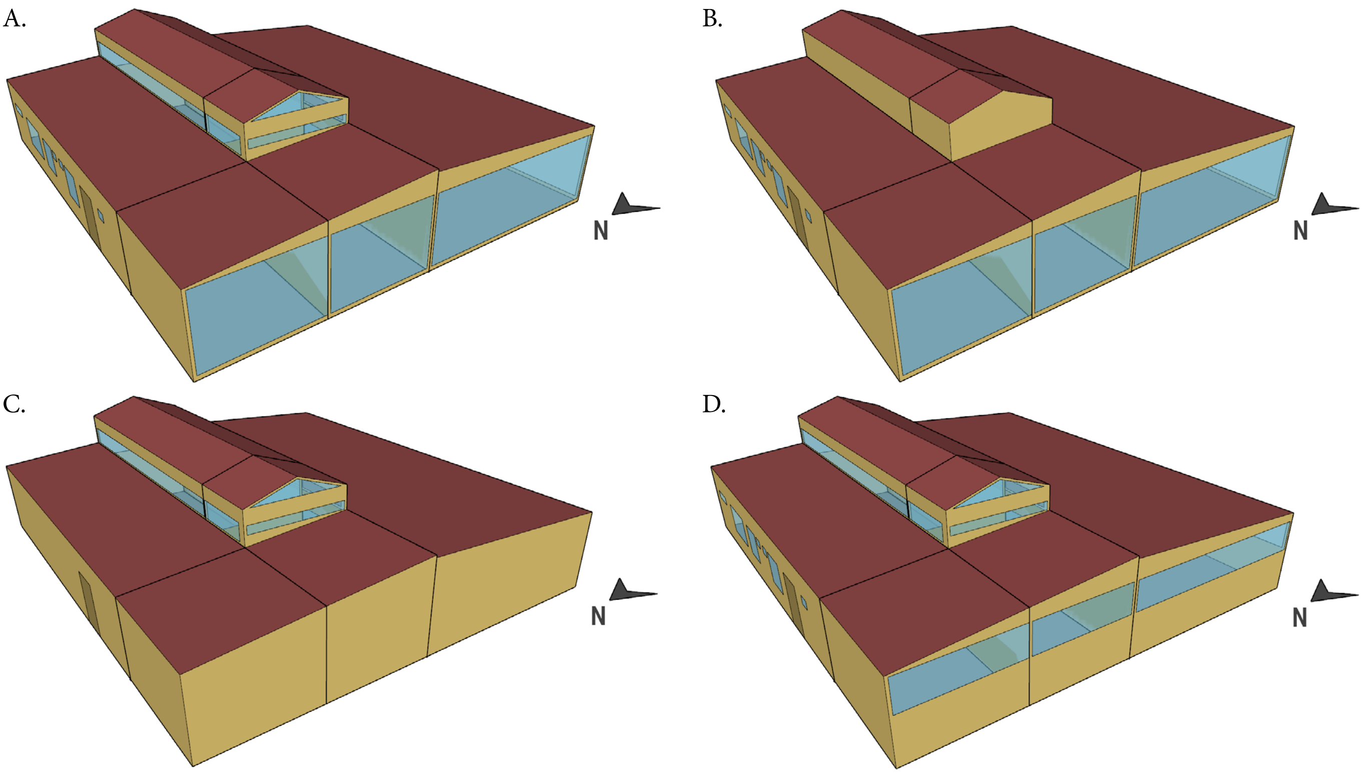
Each brick unit has an effective ventilation area of 43%. In the thermal zone designated as the transit area, the equivalent calculated area for the simplified opening of the west wall was 7.3 m². For the boiler thermal zone, the west wall was 6.8 m². In the cane area thermal zone, the equivalent areas for the west and east walls were 14 m², while for the south wall of the same zone, the area was 33 m².

The WBGT index is used to evaluate the comfort of the working environment (MinTrabajo, 1979; MinTeP, 2021). The calculation for internal environments is carried out using Eq. 2, where the WBGT index is in °C.

Table 5. Simulated treatments

Treatments	Cover material			Perimeter enclosure			Lantern window	
	Z	F	B	Open perimeter	Solid brick	Perforated brick	Open	Closed
T1	X			X			X	
T2		X		X			X	
T3			X	X			X	
T4	X			X				X
T5		X		X				X
T6			X	X				X
T7	X				X		X	
T8		X			X		X	
T9			X		X		X	
T10	X					X	X	
T11		X				X	X	
T12			X			X	X	

Z - Zinc; F - Fiber cement; B - Clay ceramic; T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, and T12 - treatments



T1, T2, and T3 - Perimeter enclosure and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; T4, T5, and T6 - Perimeter enclosure open and lantern window closed, with each covered in zinc, fiber cement, and clay ceramic, respectively; T7, T8, and T9 - Perimeter enclosure of solid brick, lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; and T10, T11, and T12 - Perimeter enclosure of perforated brick and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively

Figure 3. Treatment geometries: T1, T2, and T3 (A); T4, T5, and T6 (B); T7, T8, and T9 (C); and T10, T11, and T12 (D)

$$\text{WBGT} = 0.7T_{wb} + 0.3T_{bg} \quad (2)$$

Where:

T_{wb} - wet-bulb temperature (°C); and,

T_{bg} - black globe temperature (°C).

The simulations were carried out based on the occupancy schedule in each thermal zone, for the twelve treatments. The EnergyPlus™ 9.6 software does provide the WBGT index as an output variable, so it was calculated from other software output variables. To obtain the wet-bulb temperature (T_{wb}), Eq. 3 was used, as defined by Stull (2011).

$$\begin{aligned} T_{wb} = {} & T_{db} \times a\tan\left[0.151977 \times \left(RH + 8.313659\right)^{\frac{1}{2}}\right] + \\ & + a\tan\left(T_{db} + RH\right) - a\tan\left(RH - 1.6763310\right) + \\ & + 0.00391838 \times \left(RH\right)^{\frac{3}{2}} \times a\tan\left(0.023101\right) RH - \\ & - 4.686035 \end{aligned} \quad (3)$$

Where:

RH - relative air humidity (%), which is a function of the dry bulb temperature and the relative air humidity; and,

T_{db} - dry bulb temperature (°C).

To obtain the temperature of the black globe, Eq. 4 was used, as defined by Lamberts et al. (2014). The mean radiant temperature (MRT) is an output variable of the software.

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

Where:

MRT - mean radiant temperature (°C); and,

T_g - temperature of the black globe (°C).

To establish the tolerance limits of workers to heat exposure according to the parameters of the WBGT index, it is necessary to know the metabolic rate of the workers. In the context of this agro-industry, the work is classified as heavy, involving intermittent activities such as lifting, pushing, and dragging, for which a value of 512 W was assumed (MinTeP, 2021).

Table 6 outlines the tolerance limits of workers for heat exposure during intermittent work with rest periods at the workplace, considering the WBGT index. This type of work is considered heavy and is assumed to be performed continuously (MinTeP, 2021).

Box plots were made to compare the WBGT index for the twelve treatments and their thermal zones. The line defining the 25 °C limit was used to determine the percentage of values exceeding the limit.

Results and Discussion

Table 7 shows the comparison of temperature and relative air humidity data obtained from the EnergyPlus™ 9.6 model with the experimental data of treatment T1 (control treatment or original geometry), indicating good agreement between the results (values below 0.25). It was concluded that the proposed model can be used to accurately predict the hygrothermal behavior inside the facility (ASTM, 2019).

Figure 4 shows thermal images during the agro-industrial process, revealing the warm environment in which the workers operate near the oven in the furnace thermal zone. Notably, surface temperatures in certain areas of this zone exceed 100 °C, mainly due to the oven and hot juices, with vapors registering temperatures above 40 °C.

Workers are exposed to these temperatures, especially at waist height, without any type of protection. Additionally, these vapors contribute to high relative air humidity levels. It is evident that the handle of the tool used to transport the juice also has temperatures higher than 40 °C, transmitting heat to the worker's hands. It is also recommended that workers wear eye protection, such as infrared goggles, during work involving exposure to high temperatures and infrared radiation to prevent potential eye damage (Pouya et al., 2018).

Table 8 shows the average WBGT index values for the twelve treatments in each thermal zone during the grinding and juice processing activities. These values help determine workers' tolerance limits to heat exposure, suggesting the need for rest periods at the workplace to restore their physiological and psychological well-being, allowing them to return to their pre-fatigue state (Zhao et al., 2017).

Table 7. Validation of the computational model for temperature and relative air humidity

Thermal zone			Average	NMSE
Furnace	Temperature (°C)	Simulation	25.08 ± 3.91	0.0075
		Measurement	24.90 ± 3.31	
	Relative air humidity (%)	Simulation	73.54 ± 4.94	0.034
		Measurement	80.17 ± 8.80	
Cane area	Temperature (°C)	Simulation	22.02 ± 3.29	0.036
		Measurement	25.57 ± 3.93	
	Relative air humidity (%)	Simulation	76.44 ± 13.77	0.034
		Measurement	80.23 ± 7.91	
Molding	Temperature (°C)	Simulation	23.74 ± 2.84	0.015
		Measurement	25.82 ± 2.97	
	Relative air humidity (%)	Simulation	67.60 ± 12.22	0.047
		Measurement	78.69 ± 8.29	

NMSE - Normal mean square error

Table 6. Tolerance limits for heat exposure in intermittent work with rest periods in the workplace according to the wet-bulb globe temperature (WBGT) index (°C)

Intermittent work regime with rest at the workplace (hourly)	Light activity (125-209 W)	Moderate activity (210-350 W)	Heavy activity (> 350 W)
Continuous work	< 30	<2 6.7	< 25.0
45 min of work; 15 min of rest	30.1-30.5	26.8-28.0	25.1-25.9
30 min of work; 30 min of rest	30.7-31.4	28.1-29.4	26.0-27.9
15 min of work; 45 min of rest	31.5-32.2	29.5-31.1	28.0-30.0
Work is not permitted without adopting appropriate control measures.	> 32.2	> 31.1	> 30.0

Source - NR 9 and MinTeP (2021)

A.

B.

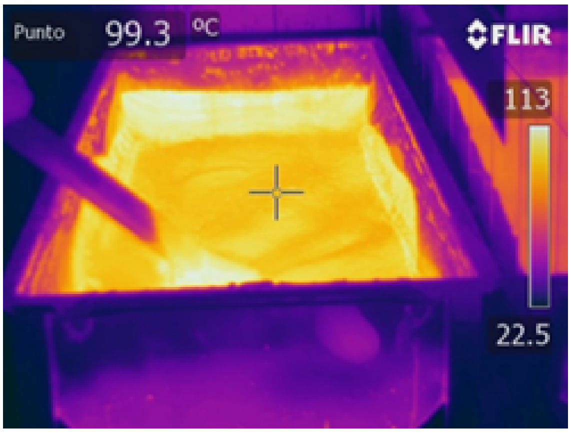


Figure 4. Thermal images within the thermal zone of the furnace during non-centrifuged cane sugar (NCS) processing: worker in the activity of stirring cane juice (A) and surface temperature of the cane juice in the evaporation process (B)

Table 8 also shows that in the furnace thermal zone, all twelve treatments exceeded the WBGT limit of 25 °C for heavy work, with average values ranging from 28 to 30.8 °C. The furnace thermal zone is the only place within the facility where work involves direct exposure to high temperatures generated by the oven, influencing the elevated WBGT index values, thus generating a condition where thermal stress is present, necessitating corrective action to prevent harm to the workers (ASHRAE, 2017; ISO, 2017).

For treatments T1, T2, and T3, 15 min of work and 45 min of rest are suggested. For T4, T5, and T6, where the lantern window is closed, higher WBGT values are observed due to reduced natural ventilation. Additionally, there is no chimney effect, which is important for the reduction of humidity and temperature, suggesting the need for appropriate control measures. This includes providing workers with protective clothing, such as aprons with reflective material and eye protection (Pouya et al., 2018).

According to MinTeP (2021), activities carried out in the five thermal zones were classified as heavy. However, the average WBGT values for the 12 treatments in the cane thermal zones, transit area, boiler, and molding area did not exceed the limit values given in Table 6. Therefore, according to Table 8, it is suggested that work is carried out continuously for all 12 treatments in these zones.

Figure 5 presents the WBGT boxplot for the twelve treatments in the thermal zones. It is noteworthy that for the furnace thermal zone (Figure 5A), more than 75% of the data for each treatment exceeds the established limit of 25 °C. This is due to the combination of high air temperature and high humidity, generated by the boiler during the NCS preparation process.

Table 8. Recommendations (R) for thermal zones based on the average wet-bulb globe temperature (WBGT) index (°C), including guidelines for continuous work (CW), minutes of work (MW), and minutes of rest (MR); work is not permitted (WNP) without adopting adequate control measures

Thermal Zone	Average WBGT (°C)									
	Cane area		Transit zone		Boiler		Furnace		Molding	
Metabolic rate	568 W		520 W		632 W		632 W		520 W	
Treatment	WBGT	R	WBGT	R	WBGT	R	WBGT	R	WBGT	R
T1	21.1	CW	21.7	CW	22.2	CW	28.0	15 MW 45 MR	22.1	CW
T2	20.8	CW	21.1	CW	21.8	CW	28.3	15 MW 45 MR	21.4	CW
T3	21.0	CW	21.5	CW	22.1	CW	28.2	15 MW 45 MR	21.8	CW
T4	21.6	CW	21.8	CW	22.5	CW	30.3	WNP	22.3	CW
T5	21.4	CW	21.2	CW	22.2	CW	30.8	WNP	21.7	CW
T6	21.6	CW	21.5	CW	22.4	CW	30.6	WNP	22.0	CW
T7	23.4	CW	23.0	CW	24.2	CW	29.4	15 MW 45 MR	22.1	CW
T8	23.1	CW	21.8	CW	23.8	CW	29.8	15 MW 45 MR	21.4	CW
T9	23.3	CW	22.5	CW	24.1	CW	29.7	15 MW 45 MR	21.8	CW
T10	21.3	CW	21.8	CW	22.7	CW	28.1	15 MW 45 MR	22.0	CW
T11	21.0	CW	21.1	CW	22.3	CW	28.5	15 MW 45 MR	21.4	CW
T12	21.2	CW	21.5	CW	22.5	CW	28.4	15 MW 45 MR	21.8	CW

T1, T2, and T3 - Perimeter enclosure and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; T4, T5, and T6 - Perimeter enclosure open and lantern window closed, with each covered in zinc, fiber cement, and clay ceramic, respectively; T7, T8, and T9 - Perimeter enclosure of solid brick, lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; and T10, T11, and T12 - Perimeter enclosure of perforated brick and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively

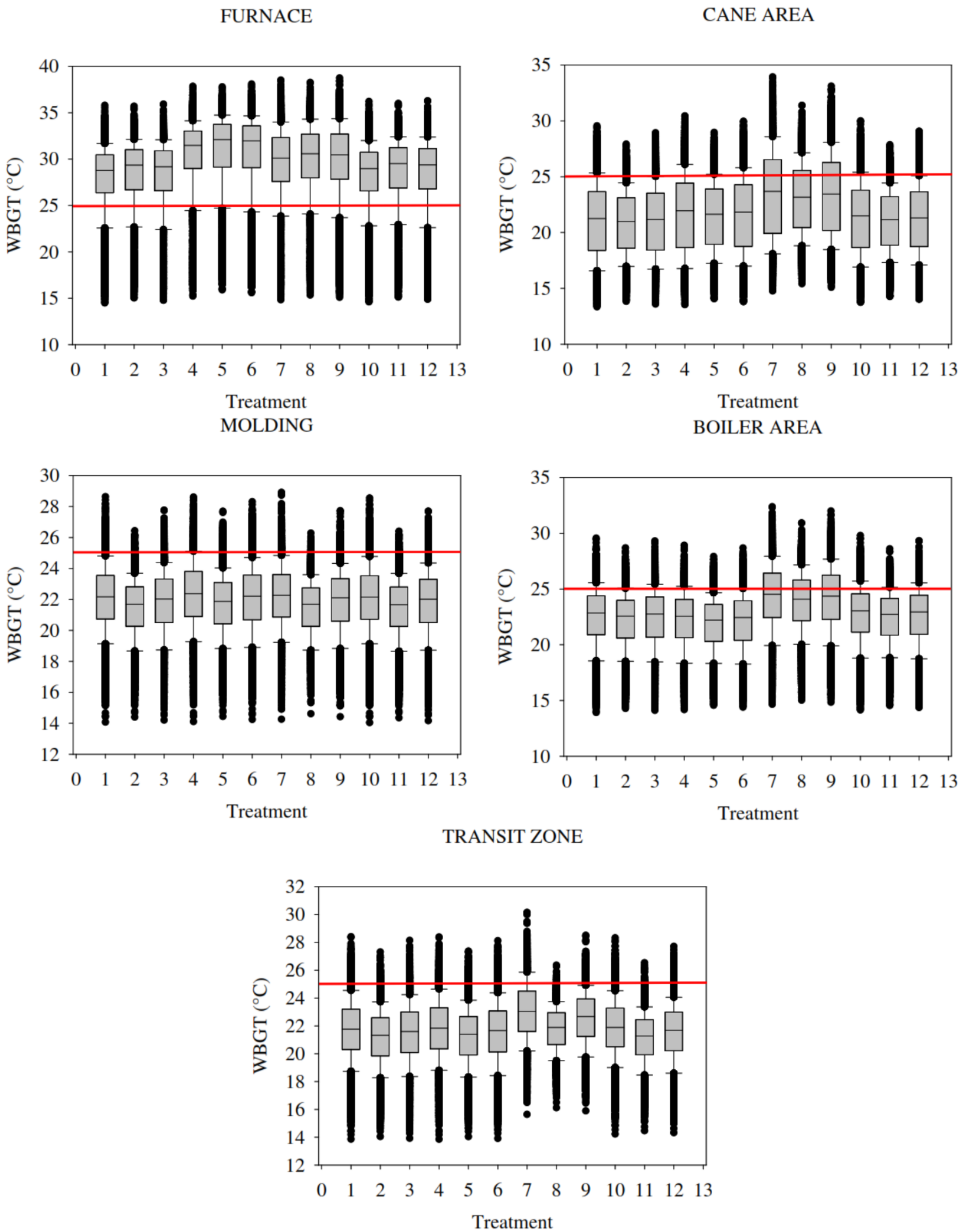


Figure 5. Boxplots of wet-bulb globe temperature (WBGT) index in thermal zones: furnace (A), cane area (B), molding (C), boiler area (D), and transit zone (E)

Figure 5B shows the boxplot of the WBGT index for the treatments in the cane area thermal zone. For treatments T7, T8, and T9 the median WBGT index is higher than the others (23.7, 23.2, and 23.4 °C, respectively), highlighting the effect of closed walls in reducing energy transfer and vapor mass due to limited natural ventilation.

Conversely, Figures 5C and E show that in the molding and transit area thermal zones, the median WBGT index is below

Table 9. Percentage of values that exceed the 25 °C limit of the wet-bulb globe temperature (WBGT) index

Treatment	Thermal zone				
	Furnace	Transit area	Molding	Cane area	Boiler
Schedule	6:00. to 19:00	00:00 to 24:00	7:00 to 20:00	00:00 to 24:00	6:00 to 19:00
T1	83.11	6.75	8.22	12.29	16.24
T2	83.54	2.43	1.04	5.64	11.04
T3	82.86	5.01	4.62	10.28	15.07
T4	89.12	7.40	11.23	19.26	12.41
T5	89.53	3.01	3.58	12.31	6.46
T6	88.81	5.75	7.63	17.84	10.65
T7	87.36	19.00	8.83	39.01	43.62
T8	88.08	5.73	0.68	31.02	36.44
T9	87.20	9.22	4.36	36.57	41.12
T10	84.19	6.14	8.06	13.32	18.79
T11	84.42	0.65	0.96	5.29	12.04
T12	83.72	3.31	4.52	11.00	17.06

T1, T2, and T3 - Perimeter enclosure and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; T4, T5, and T6 - Perimeter enclosure open and lantern window closed, with each covered in zinc, fiber cement, and clay ceramic, respectively; T7, T8, and T9 - Perimeter enclosure of solid brick, lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively; and T10, T11, and T12 - Perimeter enclosure of perforated brick and lantern window open, with each covered in zinc, fiber cement, and clay ceramic, respectively

the limit of 25 °C across all treatments. However, it is observed that a low percentage of data is above the limit.

In the boiler area (Figure 5D), the treatments T7, T8, and T9 exhibit higher median index values of 24.5, 24.1, and 24.4 °C, respectively, indicating that a distribution with closed walls is not advisable.

Table 9, similar to the box plots, shows the percentage of WBGT values exceeding 25 °C for the 12 treatments. While average WBGT values of the cane, transit area, boiler, and molding thermal zones are below the 25 °C limit, this does not rule out occasional heat stress in these zones. This is particularly true during the hottest hours of the day when the temperature difference with the external environment becomes smaller, hindering efficient heat transfer. For the furnace thermal zone, it is evident that on average, 82% of the time the WBGT values exceed the 25 °C limit.

To lessen the negative impact that high heat and steam production in agro-industries have on laborers and processed goods, more research on bioclimatics and comfort is required (Guerra-García et al., 2022).

Conclusions

1. The furnace thermal zone exhibits the most unfavorable bioclimatic behavior, regardless of the configuration of natural ventilation, leading to potential heat stress for workers due to the high air temperature and humidity during the cane juice evaporation process.

2. The recommendations include incorporating rest breaks or active strategies, such as mechanical ventilation to support the removal of steam and hot air evacuation, thereby improving microclimatic conditions in the furnace thermal zone.

3. Installations without perimeter walls demonstrated the lowest wet-bulb globe temperature index as a result of a larger ventilation area, which improves the conditions for the mass transfer of steam and heat to the exterior. This suggests that these types of facilities should be open on their perimeter and feature open lantern windows or roofs with openings.

4. In facilities or areas that generate a high amount of heat, as in this case, a larger ventilation area and materials with high thermal conductivity are suggested, mainly in the cover to facilitate efficient heat transfer to the outside. In this instance, the zinc roof in the furnace area performed the best.

5. Future research should consider measuring workers' metabolic rate during non-centrifuged cane sugar preparation, as well as conducting studies using aluminized aprons, gloves, and infrared goggles as protective clothing.

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Literature Cited

ABNT - Associação Brasileira de Normas Técnicas. NBR ISO 10456: Materiais e produtos de construção - Propriedades higrotérmicas - Valores e procedimentos de projeto tabulados para determinar valores térmicos declarados e de projeto. 2022. Available on: <https://www.normas.com.br> Accessed on: January 2023.

Alarcón, A. L.; Palacios, L. M.; Osorio, C.; César Narváez, P.; Heredia, F. J.; Orjuela, A.; Hernanz, D. Chemical characteristics and colorimetric properties of non-centrifugal cane sugar ("panela") obtained via different processing technologies. Food Chemistry, v.340, e128183, 2021. https://doi.org/10.1016/j.foodchem.2020.128183

Aldahhan, R. A.; Stanton, P. G. Heat stress response of somatic cells in the testis. Molecular and Cellular Endocrinology, v.527, e111216, 2021. https://doi.org/10.1016/j.mce.2021.111216

ASHRAE - American Society of Heating, Refrigerating and Air Conditioning Engineers. ASHRAE Handbook Fundamentals 2017. ASHRAE Inc. 2017. Available on: <https://www.ashrae.org/technical-resources/ashrae-handbook>. Accessed on: February 2021.

ASTM - American Society for Testing and Materials. Standard Guide for Statistical Evaluation of Indoor Air Quality Models (D5157-19). 2019. Available on: <https://global.ihs.com/doc_detail.cfm?document_name=ASTM D5157&item_s_key=00137897>. Accessed on: May 2021.

Calixto-Aguirre, I.; Huelsz, G.; Barrios, G.; Cruz-Salas, M. V. Validation of thermal simulations of a non-air-conditioned office building in different seasonal, occupancy and ventilation conditions. Journal of Building Engineering, v.44, e102922, 2021. https://doi.org/10.1016/j.jobe.2021.102922

DNP - Departamento Nacional de Planeación de Colombia. Proyecto tipo de construcción de trapiches paneleros. 2017 v.2. Available on: https://proyectostipo.dnp.gov.co/images/pdf/Trapiches/PTtrapiches.pdf

Guerra-García, L. M.; Osorio-Hernández, R.; Osorio-Saraz, J. A.; Carlo, J. C.; Damasceno, F. A. Bioclimatic performance of wet coffee processing facilities: conditions for workers and coffee. Revista Facultad Nacional de Agronomía Universidad Nacional de Colombia, v.75, p.9763–9772, 2022. https://doi.org/https://doi.org/10.15446/rfnam.v75n1.96247

Gungor, S.; Cetin, M.; Adiguzel, F. Calculation of comfortable thermal conditions for Mersin urban city planning in Turkey. Air Quality, Atmosphere and Health, v.14, p.515–522, 2021. https://doi.org/10.1007/s11869-020-00955-y

IDEAM - Instituto de Hidrología Meteorología y Estudios Ambientales. Atlas climatológico de Colombia. 2021. Available on: <http://atlas.ideam.gov.co/visorAtlasClimatologico.html>. Accessed on: February 2021.

IGAC - Instituto Geográfico Agustín Codazzi. Cartografía básica. 2022. Available on: <https://www.colombiaenmapas.gov.co/>. Accessed on: February 2021.

ISO - International Organization for Standardization. Ergonomics of the thermal environment - Assessment of heat stress using the WBGT (wet bulb globe temperature) index (ISO 7243:2017). Distributed through American National Standards Institute (ANSI). 2017. Available on: <https://www.iso.org/standard/67188.html>. Accessed on: February 2021.

Lamberts, R.; Dutra, L.; Pereira, F. O. R. Eficiência energética na arquitetura. 3.ed. Pro-Livros, 2014. 366p. https://labeee.ufsc.br/en/node/69

Mekjavic, P. J.; Tipton, M. J.; Mekjavic, I. B. The eye in extreme environments. Experimental Physiology, v.106, p.52–64, 2021. https://doi.org/10.1113/EP088594

MinTeP - Ministério do Trabalho e Previdência Portaria. SEPRT n.º 8.873, de 23 de julho de 2021 - Norma Regulamentadora N° 09 - ANEXO III CALOR. 2021. Available on: <https://www.gov.br/trabalho-e-emprego/pt-br/acesso-a-informacao/participacao-social/conselhos-e-orgaos-colegiados/comissao-tripartite-partitaria-permanente/arquivos/normas-regulamentadoras/nr-09-atualizada-2021-com-anexos-vibra-e-calor.pdf>. Accessed on: November 2021.

MinSalud - Ministerio de la Protección Social de Colombia. Resolución Numero 779 de 2006 del 17 de marzo: Por la cual se establece el reglamento técnico sobre los requisitos sanitarios que se deben cumplir en la producción y comercialización de la panela para consumo humano y se dictan otras disposiciones. Diario Oficial de la Republica de Colombia N° 46.223 del 17 de marzo de 2006. 2006. Available on: <https://www.minsalud.gov.co/sites/rid/Lists/BibliotecaDigital/RIDE/DE/DIJ/Resolucion-779-de-2006.pdf>. Accessed on: June 2021.

MinTrabajo - Ministerio de Trabajo y Seguridad Social de Colombia. Resolución 2400 de 1979: Por el cual se establecen disposiciones sobre vivienda, higiene y seguridad industrial en los establecimientos de trabajo. 1979. Available on: <https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=53565>. Accessed on: June 2021.

Morris, N. B.; Jay, O.; Flouris, A. D.; Casanueva, A.; Gao, C.; Foster, J.; Havenith, G.; Nybo, L. Sustainable solutions to mitigate occupational heat strain - An umbrella review of physiological effects and global health perspectives. Environmental Health: A Global Access Science Source, v.19, p.1–24, 2020. https://doi.org/10.1186/s12940-020-00641-7

Morrissey, M. C.; Brewer, G. J.; Williams, W. J.; Quinn, T.; Casa, D. J. Impact of occupational heat stress on worker productivity and economic cost. American Journal of Industrial Medicine, v.64, p.981–988, 2021. https://doi.org/10.1002/ajim.23297

Pouya, A. B.; Mosavianasl, Z.; Ajvadi, A. N. Evaluation of exposure to the radiation and the effect of using eye shield by the employees at iron works. Pakistan Journal of Medical and Health Sciences, v.12, p.1786–1788, 2018. Available on: https://pjmhsonline.com/2018/oct_dec/pdf/1786.pdf

Saafi, K.; Daouas, N. Energy and cost efficiency of phase change materials integrated in building envelopes under Tunisia Mediterranean climate. Energy, v.187, e115987, 2019. https://doi.org/10.1016/j.energy.2019.115987

Stull, R. Wet-bulb temperature from relative humidity and air temperature. Journal of Applied Meteorology and Climatology, v.50, p.2267–2269, 2011. https://doi.org/10.1175/JAMC-D-11-0143.1

Vásquez, V.; Lucía, M.; Amaya, A.; Ricardo, L. Diagnóstico de las condiciones de trabajo, en los trapiches del municipio de Chitaraque (Boyacá). El Hombre y La Máquina, v.41, p.45–55, 2013. Available on: https://www.redalyc.org/articulo.oa?id=47828416007

Watson, C.; Troynikov, O.; Kuklane, K.; Nawaz, N. Industrial workwear for hot workplace environments: thermal management attributes. International Journal of Biometeorology, v.65, p.1751–1765, 2021. https://doi.org/10.1007/s00484-021-02130-z

Zhao, Y.; Yi, W.; Chan, A. P. C.; Chan, D. W. M. Comparison of heat strain recovery in different anti-heat stress clothing ensembles after work to exhaustion. Journal of Thermal Biology, v.69, p.311–318, 2017. https://doi.org/10.1016/j.jtherbio.2017.09.004