Assessment of thermal environment and thermal comfort in air traffic control towers

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ABSTRACT

Ensuring thermal comfort in air traffic control towers (ATCTs) is paramount, given the exacting demands of air traffic control, which require heightened levels of concentration and vigilance. ATCTs feature extensive glazed surfaces, leading to significant solar gains and heat loss within the indoor environment. To maintain thermally comfortable conditions throughout the year, air conditioning systems are employed to regulate the indoor climate, adjusting for varying thermal load. However, achieving uniform and stable thermal conditions poses a challenge due to the dynamic thermal loads inherent in the environment.

This paper aims to assess the thermal conditions and comfort levels within air traffic control towers across both winter and summer seasons. Furthermore, it seeks to evaluate the impact of glazing types and the air distribution systems on indoor thermal comfort.

Eight field measurement campaigns were conducted in four ATCTs from February 2019 to March 2020. The ATCTs are all located in France, with three single-glazed towers and one double-glazed tower. In each tower, indoor air temperature and relative humidity were monitored at different heights and locations over one-week periods during winter and summer. Supply and extract air temperatures were also monitored, alongside measurements of terminal velocities. The occupants' thermal comfort was assessed through targeted measurements of physical parameters related to thermal comfort and questionnaire surveys.

The results of the physical measurements generally indicate acceptable comfort conditions in all four towers during both winter and summer periods, with occasional issues of local discomfort related to draughts in some cases. The questionnaire results yielded a mixed response, with overall acceptable comfort conditions in winter, juxtaposed with some discomfort issues in summer. The discomforts were found to be associated with operational deficiencies in the conditioning systems that have been identified. As a result, improvement avenues have been proposed to reduce discomfort.

KEYWORDS

Thermal comfort, air traffic tower control, field measurement, air distribution system

1 INTRODUCTION

Ensuring thermal comfort in air traffic control towers (ATCTs) is paramount, given the exacting demands of air traffic control, which require heightened levels of concentration and vigilance. ATCTs feature extensive glazed surfaces, leading to significant solar gains and heat loss within the indoor environment. To maintain thermally comfortable conditions throughout the yearHVAC systems are employed to regulate the indoor climate, adjusting for varying thermal load. However, achieving uniform and stable thermal conditions poses a challenge due to the dynamic thermal loads inherent in the environment.

Different type of glazings are used in ATCTs: single or double glazing with or without solar control. The glazing has a significant impact on the energy performance of the ATCT, affecting both the energy loads and, consequently, the HVAC sizing and the annual energy consumption for heating and cooling (Richieri, et al., 2021).
This paper aims to assess the thermal conditions and comfort levels within air traffic control towers across both winter and summer seasons. Furthermore, it seeks to evaluate the impact of glazing types and the air distribution systems on indoor thermal comfort. The study is based on field measurement campaigns carried out in four ATCTs located in France, during winter and summer. The ATCTs include three single-glazed towers and one double-glazed tower.

2 METHOD

2.1 Description of the case studies

Four ATCTs were selected for the onsite measurement campaign (Figure 1): Bordeaux Airport, Roissy Airport (north and south towers), and Grenoble Airport. Table 1 presents the main characteristics the monitored ATCTs.

ATCT_a **ATCT_b** **ATCT_c** **ATCT_d**

Figure 1. View of the ATCT of Bordeaux airport (a), north and south towers of Roissy airport (b and c respectively) and Grenoble airport (d)

Table 1. Main characteristics of the monitored ATCTs

	ATCT_a	**ATCT_b**	**ATCT_c**	**ATCT_d**
Shape	Circular	Circular	Circular	Square
Height	40 m	90 m	65 m	10 m
Floor area (podium area)	110 m² (65 m²)	80 m² (65 m²)	75 m² (50 m²)	34 m² (no podium)
Ceiling height	6 m	4.7 m	3.4 m	3 m
Volume	580 m³	375 m³	250 m³	102 m³
Glazing type	Single glazing	Single glazing	Single glazing	Double glazing
Glazing area	240 m²	170 m²	135 m²	45m²
Glazing slope	110°	110°	100°	107° (North at 90°)
Solar shading	Interior solar screen	Interior solar screen	Interior solar screen	Interior solar screen
# of controllers	6	9	8	5

Only the ATCT at Grenoble is double-glazed, while the other three are single-glazed, which is the majority of ATCTs in France. The ATCT at Bordeaux Airport is the largest with the highest glazing area. The north and south ATCTs at Roissy Airport are slightly smaller but have a high density of occupation, as Roissy Airport is a major European hub with intensive air traffic. Finally, the ATCT at Grenoble Airport is the smallest, with modest air traffic.

For the three ATCTs at Bordeaux and Roissy airport, the interior space is arranged with a central podium elevated by approximately 1.2 meters, which accommodates the controllers' activities, and a functional peripheral walkway for circulation and air distribution. Thus, workstations are located approximately 3 meters away from the glazing. For Grenoble airport, there is no podium and the workstations are close to the glazing.
Regarding HVAC equipment, AHUs (air handling units) are used in ATCT a, b and c, for heating, air conditioning, and ventilation, with an underfloor air distribution. Floor diffusers are located in the walkway near the glazing. For ATCT_b, there are additional floor diffusers on the podium as shown in Figure 2. Return air grilles are also located in the walkway at the floor level near the floor diffusers for ATCT_a, and in the staircase for the ATCT b and c. For the ATCT_d, there is a central heating system with hot water radiator, two ceiling air conditioners with manual adjustment and single exhaust ventilation.

Figure 2. View of the supply air units in ATCT_a, ATCT_b and ATCT_c

2.2 Measurement method

In order to assess the thermal comfort of the controllers in the ATCT, the thermal comfort indices PMV/PPD (ISO 7730, 2006) are used as recommended by (EN 16798-1, 2019) for heated and mechanically cooled buildings. As these indices characterises global thermal comfort, two additional local discomfort indices DR (draught rate) and PD (percentage dissatisfied) are used to assess the discomfort due to draught and vertical air temperature difference, respectively, that can result from the air distribution or stratification.
The PMV predicts the mean vote on the ASHRAE thermal sensation scale from cold (-3) to hot (+3) with a central neutral sensation (0) and the PPD predict the percentage of dissatisfied for a given PMV value. The indices DR and PD predict the percentage of dissatisfied due to draught and vertical air temperature difference respectively. Table 2 shows the recommended criteria for the thermal comfort indices in heated and air-conditioned spaces according to the level of expectation.

Table 2. Recommended criteria for the thermal comfort in heated and air-conditioned spaces (* recommended value during winter; ** recommended value during summer)

Position	Global comfort		Draught		Vertical t_a difference	
	PMV	PPD [%]	v_a [$m.s^{-1}$]	DR [%]	$\Delta t_{a,v}$ [°C]	PD [%]
High level	-0.2 to +0.2	6%	$0.10^{*}/0.12^{**}$ $m.s^{-1}$	10%	2°C	3%
Normal level	-0.5 to +0.5	10%	$0.16^{*}/0.19^{**}$ $m.s^{-1}$	20%	3°C	5%

AHLBORN thermal comfort station (Figure 3) was used to measure the thermal parameters required to calculate the comfort indices: air temperature (accuracy ±0.2°C), globe temperature

(accuracy ±0.2°C), relative humidity (accuracy ±2.0 %) and air velocity (accuracy ±0.04 m.s^{-1} + 0.5% of reading). These parameters were measured at the head, abdomen and ankle levels for a sitting and standing person (0.1/0.6/1.1 m and 0.1/1.1/1.7 m respectively) over a period of 20 minutes. The mean values were used to calculate the comfort indices as recommended by (ISO 7726, 2002). The measurements were carried out in each ATCT at two different positions over one day during winter and summer.
In order to assess the thermal environment and the operation of the AHUs, indoor air temperature and relative humidity (RH) were continuously monitored using Hobo dataloggers at different heights and two different locations on the podium over one-week periods during winter and summer (10 minutes timestep) (Figure 4). Supply and extract air temperatures were also monitored, alongside measurements of terminal velocities. Outdoor air temperature and RH sere also monitored.
Finally, subjective questionnaires were used to assess the perceived comfort of the controllers as recommended by (ISO 10551, 2019).
The measurement campaigns also included measurements of heat transfer through glazing using a heat flow meter, but they are outside the scope of this paper and will not be presented here. They can be found in (Moujalled, et al., 2022).

Figure 3. Thermal comfort monitoring station at the head, abdomen and ankle levels for a standing person including an omnidirectional anemometer, globe temperature, and air temperature and RH sensor

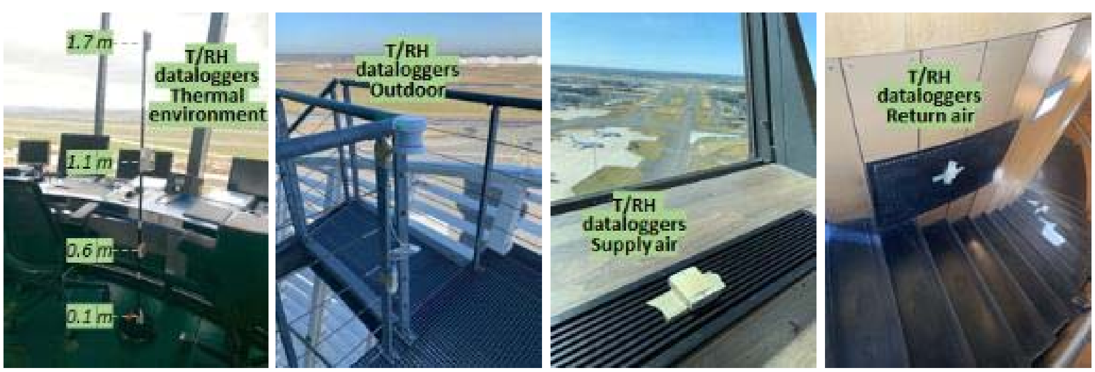

Figure 4. T/RH dataloggers for the monitoring of the podium thermal environment, outdoor air, supply return air

3 RESULTS

3.1 Analysis of AHU functioning: air supply and return

Figure 5 shows the boxplots of the supply and return air temperatures of the AHUs in the ATCT a, b and c during winter and summer. Figure 6 shows the evolution of the air temperatures for the ATCT_a during the three hottest days of summer. Table 2 presents the main statistics of the measured air velocities of the floor diffusers.

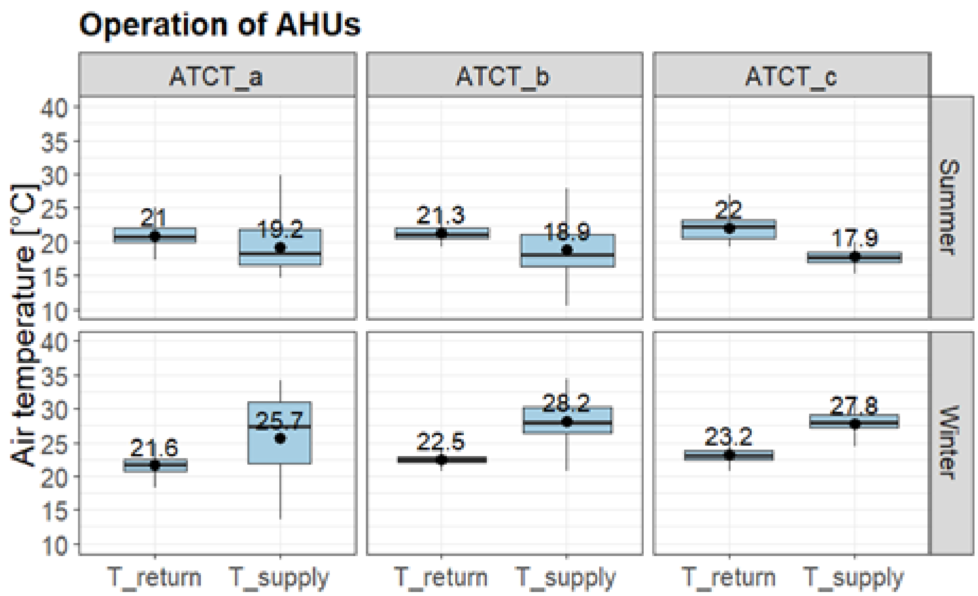

Figure 5. Boxplot with mean value of supply and return T in the ACTC a, b and c during summer and winter

The return air temperatures vary within a narrow range around an average value from 21°C to 23°C within the comfort range, depending on the heating and cooling setpoint temperatures in each ATCT. The supply air temperatures, especially in ATCT_a, vary within a wide range from 13°C to 34°C. Indeed, the AHU alternates between heating and cooling modes in both seasons, depending on the outdoor temperature and solar radiation, as shown in Figure 6. Even during the hottest days in summer, we observe a heating mode for a few hours at night with supply temperatures around 24°C, and a cooling mode for the rest of the time with supply temperatures around 15°C. This overall shows good operation of the AHU, which maintains a return air temperature around the heating and cooling setpoints of 20°C and 22°C, respectively.

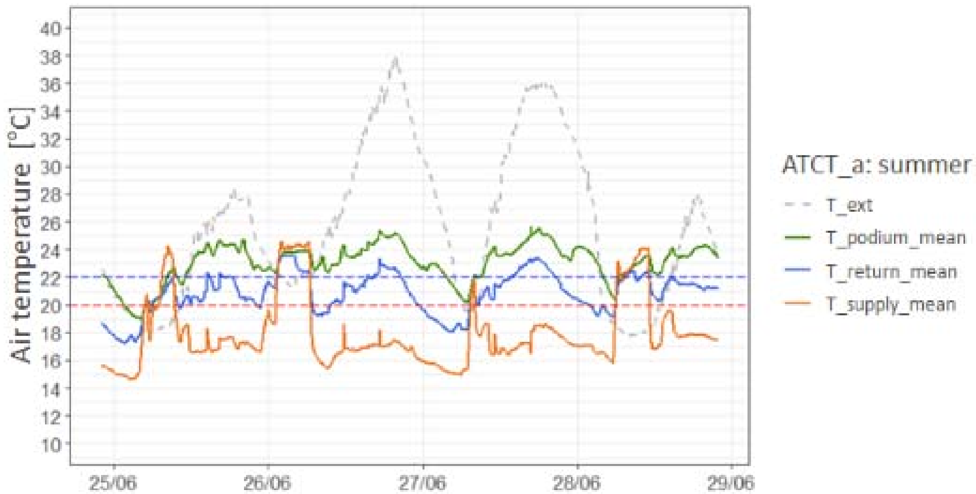

Figure 6. Evolution of air temperature in ATCT_a during the hottest days of summer

However, we observe a significant discrepancy (2°C to 4°C) between the return air temperature and the average temperature on the podium when the AHU operates in cooling mode for ATCT_a. The return air temperature varies slightly around its setpoint of 22°C, while the podium temperature rises to 26°C by the end of the day. This reveals a problem of recycling part of the cold supply air in cooling mode before reaching the podium, where the temperature remains 2°C to 4°C higher compared to the walkway. This recycling issue can be explained by the configuration of the supply diffusers and extraction grilles located face-to-face in the walkway and the low air velocity of the floor diffusers, as shown in Table 3. This introduces a bias in the cooling mode regulation of the AHU, which was based on the return air temperature significantly lower than that perceived by the controllers on the podium. Since then, the regulation has been renovated to operate according to the ambient sensors on the podium.
For the North control tower at Roissy, the cold air supply on the podium (via floor diffusers) creates a cold draft at the controllers' ankles in summer, which is a source of discomfort as discussed in section 3.3.

Table 3. Descriptive statistics of the air diffuser velocities in ATCT_a, ATCT_b and ATCT_d

		ATCT_a: walkway		**ATCT_b: walkway**		**ATCT_b: podium**		**ATCT_c: walkway**	
		Winter	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**
Supply air velocity [m.s^{-1}]	Min	0.60	0.65	0.50	0.40	0.30	0.20	1.66	1.20
	Max	2.15	2.15	1.69	1.75	0.61	0.51	3.00	1.99
	Mean	1.28	1.37	1.12	1.05	0.46	0.41	2.16	1.55
	S.D.	0.39	0.37	0.28	0.30	0.11	0.11	0.36	0.22

3.2 Analysis of the indoor thermal environment

Figure 7 and Figure 8 show the boxplots of indoor air temperature (Ta) and RH at different heights and positions in the ATCTs during winter and summer.
For ATCT_a, Ta values vary little in winter and fall within the comfort range of 20°C to 24°C, with an average around 22°C. In summer, they vary within a wider range of 19°C to 26°C, with an average around 23°C. They never exceed the upper threshold of the thermal comfort range (26°C), and they are slightly below the lower threshold (23°C), especially at night when temperatures can drop to 19°C. This likely corresponds to periods when the control tower is

unoccupied. RH values are globally in the comfort ranges and slightly exceed 60% in the summer due to the air-conditioning.

For ATCT_b, Ta values are homogeneous in winter with an average of around 23°C. They generally fall within the comfort range of 20°C to 24°C throughout the measurement period. In summer, the air temperatures on the podium are less homogeneous, with lower values at ankle level (around 21°C) than at head level (24°C). However, the differences remain within approximately 1°C of the average podium temperature, which is around 22.5°C. Overall, they vary within a wide range from 19°C to 28°C. They slightly exceed the upper threshold of the thermal comfort range in summer (26°C) on the hottest days (with more than 35°C outside), but are below the lower threshold of the comfort range (23°C) for nearly half the time, especially at night. RH values are globally in the comfort ranges.

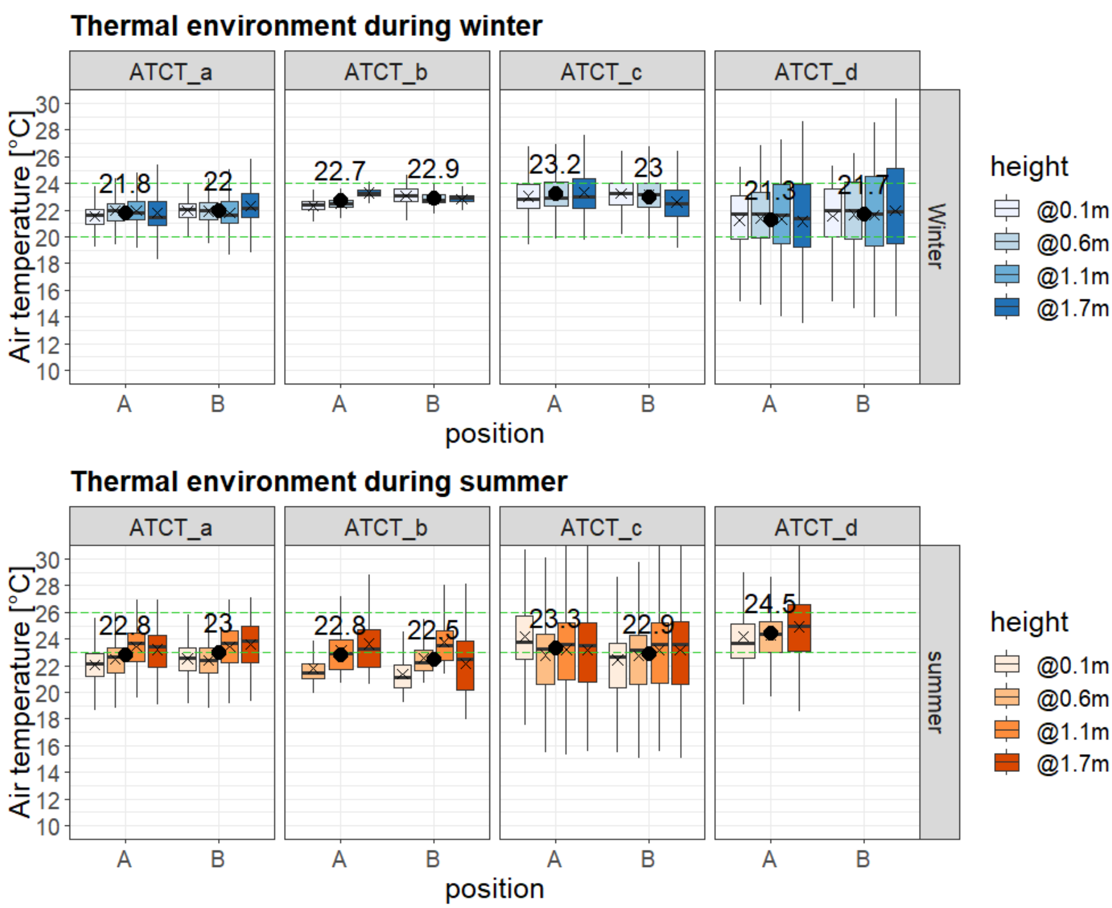

Figure 7. Boxplot with mean value (black point) of the indoor air temperatures in the ATCTs at different heights and positions

For ATCT_c, Ta values vary within a wide range from 20°C to 28°C in winter, with an average of around 23°C. They never drop below the lower threshold of the comfort range of 20°C, but they often exceed the upper threshold of 24°C in the afternoon depending on the sun (up to 28°C). In summer, the air temperatures on the podium also average around 23°C. They vary within a wider range from 19°C to 30°C. They slightly exceed the upper threshold of the thermal comfort range in summer (26°C) on the hottest days (with more than 35°C outside). However, they are below the lower threshold (23°C) for nearly half the time. Indeed, they are generally between 23°C and 26°C during the day from 9 AM to 9 PM, but from 9 PM they drop more or

less quickly to 19°C before rising again in the early morning. RH values are globally in the comfort ranges.
For ATCT_d, the situation is different with important variations during winter and summer. It is smallest ATCT with a moderate air traffic control activity and unoccupied periods. In winter, Ta values are generally homogeneous but vary significantly between 15°C (at night) and 28°C with an average of around 21°C. Ta drops below 20°C at night when the tower is unoccupied. During the day, it generally stays between 20°C and 24°C, frequently exceeding 24°C on sunny days and fluctuating more or less depending on the opening of the external door. In summer, Ta values also vary within a wide range from 19°C (at night) to 38°C (during the day, when unoccupied with 44°C outside) with an average of around 24°C. During the day and when occupied, the average Ta in the control tower generally stays within the comfort range of 23°C to 26°C, thanks to air conditioning with outdoor temperatures up to 35°C. When the outdoor temperature exceeds 35°C, Ta exceeds the 26°C threshold but remains below 28°C (with outdoor temperatures over 40°C). RH values are globally in the comfort ranges.

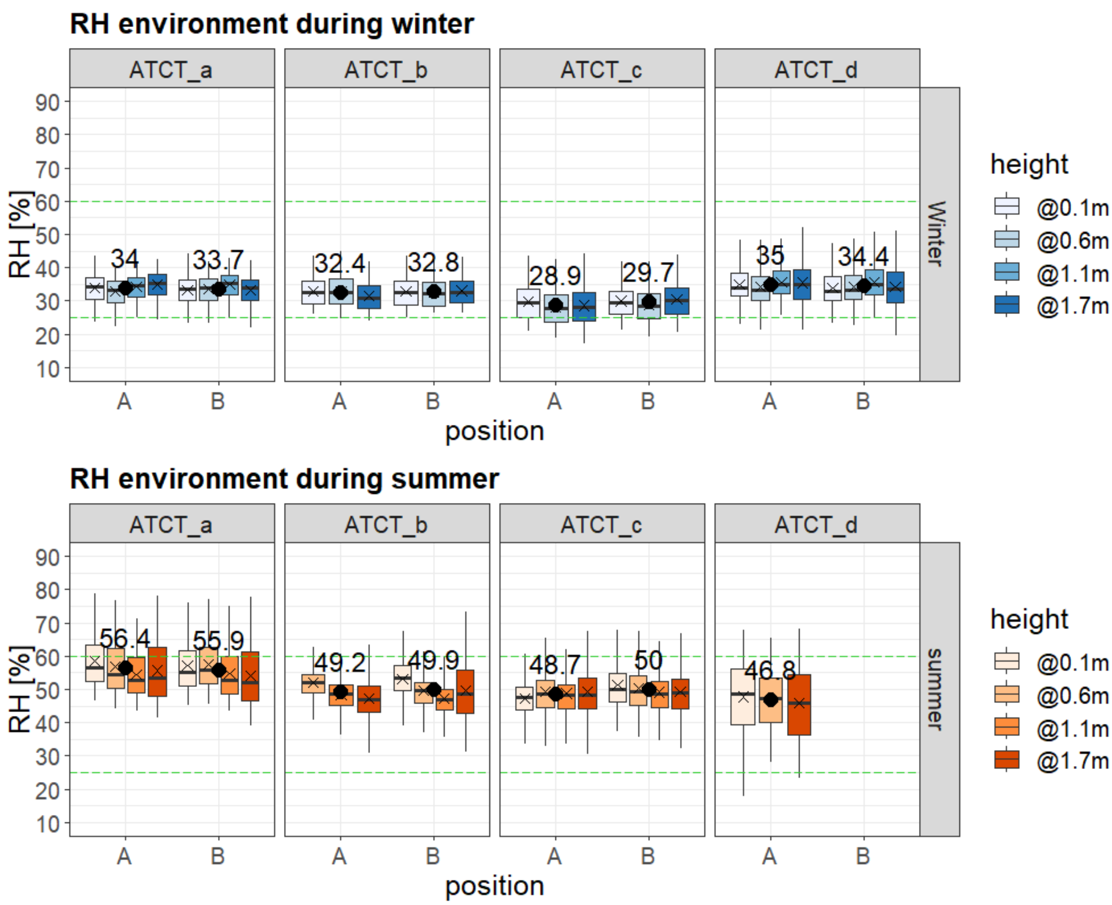

Figure 8. Boxplot with mean value of the indoor RH in the ATCTs at different heights and positions

3.3 Analysis of the thermal comfort

Table 4 presents the main results of the global comfort and local discomfort indices for a sitting person in the ATCTs during winter and summer.
In view of the global comfort and local discomfort indices, thermal comfort is generally satisfactory in the four control towers in winter and summer, with dissatisfaction rates always

below 10%, except for the ATCTs at Roissy in summer during the morning (ATCT b and c), and the ATCT_d at Grenoble in winter.

For ATCT b and c in summer, this slight discomfort is due to the cool sensation in the morning (POS1) caused by the air-conditioning. Indeed, the floor diffusers on the podium blow cold air directly at the controllers' ankles, which also creates a higher draught risk. This problem is exacerbated when the controllers are performing static activities at their stations while wearing light summer clothing. However, this cool discomfort disappears in the afternoon (POS2).

For ATCTd in winter, the situation is different as the discomfort is due to warm sensation. The measurements were performed during a sunny day with outdoor air temperature around 15°C. The controllers opened the exterior door to avoid overheating.

The feedback from the controllers through questionnaires confirms the results observed by the measurements, with overall satisfactory perceived comfort, except for the Bordeaux control tower in summer. For the latter, unlike the results of the physical measurements, the feedback from the controllers is mixed, with issues of warm discomfort (5 controllers out of 9) and dry air (7 controllers out of 9), despite air temperatures below 26°C on the podium and relative humidity frequently exceeding 60%. This discrepancy between the thermal conditions on the podium and the controllers' perception is difficult to explain given the multisensory aspect of thermal comfort and the impact of psychological factors. Exposure to solar radiation or the difficulty in finely controlling the temperature on the podium (due to the recycling of cold blown air in the corridor as discussed in section 3.1) are constraints that could interfere with the controllers' perception of thermal comfort. Lastly, we note that for the ATCT_d, the controllers mentioned the difficulty to manage the indoor temperature due to the multiplicity of HVAC systems, as well as the inertia of the central heating radiators.

Table 4. Results of the thermal comfort indices in the ATCTs during winter and summer

Tower	Period	Position	Global comfort		Draught		Vertical t_a difference	
			PMV	PPD [%]	v_a [m.s^{-1}]	DR [%]	$\Delta t_{a,v}$ [°C]	PD [%]
ATCT_a	Winter	POS1	-0.1	5.1	0.07	5.8	1.9	1.6
		POS2	-0.2	5.7	0.15	21.9	2.2	2.1
	Summer	POS1	0.3	6.5	0.08	5.1	1.2	0.9
		POS2	0.0	5.0	0.10	7.8	0.9	0.7
ATCT_b	Winter	POS1	0.2	6.1	0.04	0.0	2.2	2.0
	Summer	POS1	**-0.7**	**14.9**	**0.19**	**22.3**	2.7	3.1
		POS2	-0.5	11.2	0.08	7.1	1.4	1.0
ATCT_c	Winter	POS1	0.3	7.1	0.01	0.0	0.1	0.3
	Summer	POS1	**-0.6**	**11.8**	**0.14**	**15.7**	0.5	0.5
		POS2	0.2	5.5	0.03	0.0	1.0	0.8
ATCT_d	Winter	POS1	0.6	12.7	0.12	9.7	1.5	1.1
		POS2	**0.7**	**14.3**	**0.20**	**17.6**	1.9	1.6
	Summer	POS1	0.3	7.4	0.04	0.0	1.0	0.7
		POS2	0.5	9.2	0.07	4.2	0.9	0.7

4 CONCLUSIONS

Eight field measurement campaigns were conducted in four ATCTs from February 2019 to March 2020. These ATCTs, all located in France, include three single-glazed towers and one double-glazed tower.

In each tower, indoor air temperature and relative humidity were monitored at different heights and locations over one-week periods during winter and summer. Supply and extract air temperatures were also monitored, alongside measurements of terminal velocities. The occupants' thermal comfort was assessed through targeted measurements of physical parameters related to thermal comfort and questionnaire surveys.
The results of the physical measurements generally indicate acceptable comfort conditions in all four towers during both winter and summer periods, with occasional issues of local discomfort related to draughts in some cases. The questionnaire results yielded a mixed response, with overall acceptable comfort conditions in winter, juxtaposed with some discomfort issues in summer.
Due to the small sample size, with only one double-glazed ATCT smaller than the other three, it was not possible to conclude on the impact of glazing type on thermal comfort. However, thanks to the HVAC systems, the indoor thermal conditions were generally within comfort ranges. The main observed discomfort issues were primarily related to operational deficiencies in the HVAC systems, particularly the air distribution of the AHUs, which caused issues with recycling supplied cool air and localized cold discomfort.
As a result, improvement avenues have been proposed to reduce discomfort, and some recommendations were integrated into a design specification guide for HVAC installations in control towers. These include air diffusion with minimum pressure for minimum velocity, a penalty coefficient for glazing losses, temperature setpoints for sizing, and consideration of temperature stratification in cooling.

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6 REFERENCES

EN 16798-1, 2019. *Energy performance of buildings - Ventilation for buildings - Part 1 : indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M.* France: AFNOR.

ISO 10551, 2019. *Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments.* France: AFNOR.

ISO 7726, 2002. *Ergonomics of the Thermal Environment - Instruments for measuring physical quantities.* France: AFNOR.

ISO 7730, 2006. *Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD indices and Local Thermal Comfort Criteria: International Organization for Standardization..* France: AFNOR.

Moujalled, B., Moral, N., Cueille, R. & Chevallier, A., 2022. *Evaluation in situ du confort thermique: Suivi instrumenté de 4 vigies,* Bron, France: Cerema.

Richieri, F., Moujalled, B. & Nicolle, E., 2021. Design of high-performance control towers: Importance and difficulty of achieving duct and envelope airtightness. *12th International BUILDAIR Symposium.*