Natural ventilation in office buildings – an experimental study of a reduced scale model

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Abstract

In Mediterranean climates, instead of using mechanical systems to cool the service buildings, a passive ventilation technique benefits from the fresh ambient air, during nighttime, to ventilate the offices and, thus, reduces their overall energy consumption. However, modern constructions are often equipped with decorative components, like the suspended ceilings (SCs), which are obstacles to the desired thermal exchange between the occupation zone and the slab.

This constructive solution, called Night Ventilation (NV), motivates the goal of the present thesis: to experimentally investigate the optimization of the use of a SC that does not totally cover the slab. More precisely, the problem is explored by running experiments in a reduced scale model of an office building, analyzing results for the heating and the cooling phases.

The results confirm that, as it was found in previous works, implementing SCs with peripheral gaps, in the reduced scale office, is an effective use of NV on reducing the next day temperature peak. The contribution of this thesis is the analysis of the cooling pattern in the model. Indeed, the results indicate that the size of the peripheral gap between the side walls and the SC does not influence drastically the cooling pattern of the room. As a matter of fact, in all the tested configurations, the areas closer to the supply and exhaust air openings cool down faster than the others. However, it has been found that SCs with peripheral gaps induce a more homogenized cooling than the complete SC.

1. Introduction

While our available resources of energy are limited, the world's energy demand is constantly rising because of the development and the growth of our societies [1]. It is a well-known fact now that the building sector represents a huge share of the total final energy consumption. This is due to the increase of the time spent indoor, the necessity to satisfy the comfort levels, and the enhancement of building services. Among building services, space heating, ventilation and cooling account for more than 40% of the overall energy use in commercial buildings [2]. However, these systems are needed because it is important for the building occupants' health [3] and performance in office tasks [4]. Consequently, the challenge lies in maintaining satisfactory indoor air quality (IAQ) and thermal comfort for large space building, in an energy efficient way [5].

Night ventilation (NV) or nocturnal convective cooling is an efficient passive solution to cool buildings and presents a significant alternative to traditional air conditioning system [6]. The incoming cool air decreases the indoor air temperature, together with the structural elements temperature, and replaces contaminated indoor air. So, the building structure is used as thermal energy storage in the cooling period (CP): during nighttime it is cooled down thanks to the wind. The following day, it absorbs the heat generated by humans and devices, during what is called the heating period (HP). In that respect, heat transfer occurs twice in this strategy: from building elements (e.g. ceiling, floor, walls) to circulating air during CP, and the reverse transfer happens in the HP. Consequently, NV is particularly appropriate for office buildings, since they are unoccupied at night, unlike households.

Researches related to NV [6-8], undertaken worldwide since 1997, and reported by Solgi et al. [9], aimed to identify the key parameters of NV, in order to enhance the potential of this technique. To sum up, the exact contribution of NV for a specific building is a function of several parameters. These include the building structural and design characteristics, the climatic ambient conditions, the air flow rate entering in the room during nighttime, the efficient coupling of air flow with the thermal mass of the building and the assumed operational conditions [6]. In addition, the most essential benefits of NV are reducing peak air-temperatures of the building during the day, and creating a time lag between the occurrence of external and internal maximum temperatures [10, 11].

Furthermore, several investigations [12-20] converge in the sense that the greater the thermal mass of the building exposed to the airflow, the greater the night cooling efficiency is. Nevertheless, modern constructions were not designed to use efficiently their thermal mass. Actually, it is common to find components acting as insulators. Indeed, they prevent the thermal mass to be exposed to the occupied zone, leading to an inefficient heat exchange, and influence the air flow through the room, consequently affecting its ventilation effectiveness. For instance, a suspended ceiling (SC) below the slab exhibits an incorrect exposure of the slab for cooling purposes. Fortunately, since this issue emerged, efforts have been done on using this structural element as part of a thermal storage system. Consequently, studies looking for a way to conjugate SCs with satisfactory levels of indoor comfort were carried out [15-19, 21]. The most important observation is that an air permeable SC may have some advantages, since it allows mixing between the air below and above it. So, a SC without full coverage improves thermal cooling.

The present experimental study is a follow up of the work of Lança et al. [22] that aims to characterize the effectiveness of a SC that does not totally cover the slab, thus allowing the air flow and the direct heat exchanges in the space between the SC and the slab, called plenum. For this purpose, the same reduced scale model of an office building, already available and equipped with the instrumentation, was employed in this thesis. So, the particularities of the night cooling strategy in [22] are the use of a SC with gaps and the openings for ventilation located above it. More precisely, the first goal is to confirm the conclusions of Lança et al. [22] regarding the HP, using several designs of a SC in the model. Secondly, it is important to focus on the CP and analyze the influence of the SC, since it is the lack of knowledge on this phase that motivates this work.

2. Methodology

2.1. Experimental set-up

The experimental set-up used in the present work is installed in a building belonging to the Civil Engineering National Laboratory (LNEC - Laboratório Nacional de Engenharia Civil), located in Lisbon, with dimensions of $Lx \times Ly \times Lz = 0{,}75m \times 1{,}25m \times 0{,}43m$ and orthogonal shape. The reduce scale model is composed of four walls and the floor, all made of extruded polystyrene insulation panels, the ceiling, a concrete slab, and the SC, in cardboard. In this thesis, three different SCs are used and experiments without SC are also conducted, for comparison purposes. The peripheral gap between the SC and the surrounding walls aims to enhance the night cooling technique. Indeed, this space allows the air to circulate between the plenum, which is the area between the concrete slab and the SC, and the occupation zone, which is the area below the SC, shown in Figure 2.1.The sizes of the gaps in directions x and y are defined by percentages 0%, 2,5% x 2,5% and 7,5% x 10% of the longest dimension of the room ($1{,}25\ m$). The reason for the use of SCs with peripheral gaps in the present work is twofold. First, the SC is still hiding the technical components that can be found in buildings (cables and pipes, for example) from the occupants view because it partly covers the ceiling. Secondly, those gaps promote heat and mass transfer between the zones above and below. In this way, the heat exchange with the concrete slab is more efficient.

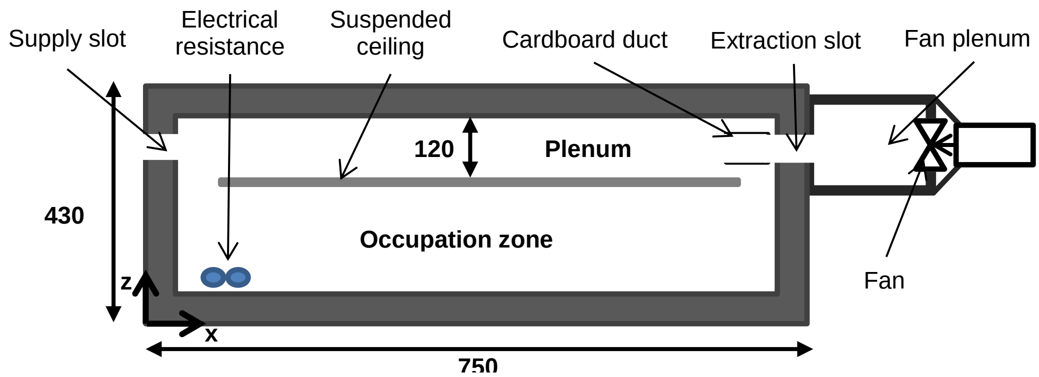


Figure 2.1 - Schematic of the experimental set-up (dimensions in millimeters).

In order to simulate the internal heat, a cylindrical electrical resistance (Figure 2.2) is releasing a heat load of 62 or 100 Watts (W) on during the HP, which is assumed to be from 8 a.m. to 8 p.m. The two pipe-type resistances, of 1 meter long, are situated horizontally, on the floor, close to the wall of the air inlet side. Also, the model is cross-ventilated because it has two identical openings located at opposite walls so the cool incoming air passes through the enclosure. The supply and the extraction rectangular shaped slots are located above the SC, which is $120\ mm$ below the lower surface of the concrete slab. This configuration, called “Opening 1” or “O1”, originates a wall jet along the slab [22]. From 8 p.m. to 8 a.m. the air supply slot is passive, whereas the extraction slot is equipped with a fan, which extracts air from the plenum to the exterior, and allows admission of ambient cool air from the supply slot. So, the cooling period (CP) also lasts 12 hours, during which an airflow of $1{,}1$ or $2{,}05\ m/s$ cools down the enclosure. The air outlet opening, where the fan is mounted, is connected to a plenum, which allows the pressure at the extraction slot to be approximately uniform and minimizes flow disturbances [22]. The electrical resistance and the fan are regulated by a control post, which is programmed to automatically start and stop them at the requested hours.

2.2. Similitude between full scale and reduced scale rooms

Geometric, kinematic and thermal similarities between the full scale room and the reduced scale model should be preserved to be able to make trustworthy conclusions at full scale from reduced scale experiments. First of all, geometrical similarity between the system being simulated and the experiments is guaranteed. Secondly, during the HP, the electrical resistance is on, and the internal flow is dominated by the heat source thermal plume and, consequently, the Grashof number, noted Gr, is the relevant dimensionless parameter. Maintaining the same Grashof number is not feasible [22]. Therefore, the same heating power per unit area of the floor was considered, yielding a modified Grashof number of 5×10^9 in the reduced scale model, which allows the flow to be fully turbulent. Thirdly, during the CP, the fan is extracting air from the enclosure, and the internal flow is dominated by the forced convection due to wind cross ventilation and, therefore, the Reynolds number, noted Re, is the key nondimensional parameter. In the present thesis, lower velocities than the one used in [22], namely $1{,}1$ and $2{,}05\ m/s$, are used, which still guarantee a turbulent flow.

2.3. Instrumentation

For each test, three different types of measurements were performed using specific equipment:

- the air velocity, evaluated by one anemometer (TSI, model 8455) always at the same location of the entry plane of the cardboard duct. The latter point is called the reference point, and its velocity is named u_{ref}.This anemometer is located above the SC.

- the heat flux transferred by conduction through the slab, measured by two heat flux sensors (Hukseflux, model HFP01) attached to the lower surface of the slab, F1 and F2, measured. Only the results from F1, located at $x = L_x/6$, $y = L_y/2$, i.e., just downstream of the supply slot, are analyzed.

- the air temperature inside the model, measured by six vertical columns, of seven thermocouples (TCs) each, see Figure 2.3. The slab temperature, read by fourteen TCs are attached to the lower surface of the slab and eight others are measuring the temperature of the concrete slab at different depths. The resistance temperature, noted T_R, is also determined by a TC. Finally, the laboratory temperature T_{lab} is measured by a TC far away from the heat released by the instrumentation.

The data acquisition was made thanks to two data loggers (Datataker, models DT 515) and one channel expansion module (Datataker, CEM).

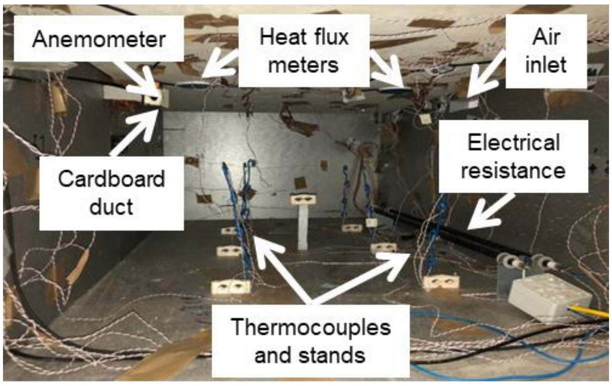


Figure 2.2 - Inside view of the reduced scale model with its equipment.

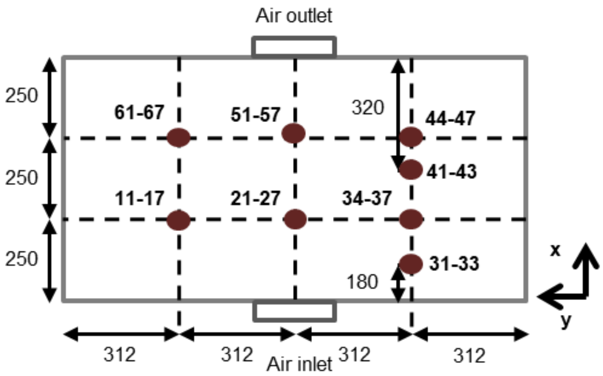


Figure 2.3 - Location of the thermocouples by columns (dimensions in millimeters).

2.4. Uncertainty of the measurements

There are two methods to evaluate the uncertainty of the measurements [23]: a Type B uncertainty is estimated thanks to manufacturer's specifications and it was used for the electrical power measurement and the heat flux measurement; a type A uncertainty is evaluated from the experimental standard deviation that characterizes the measurement, and it was used to estimate the expanded uncertainty of the temperature and air velocity. The measurement chain used in the experiments was calibrated and the following expanded uncertainties were estimated, considering a 95% confidence interval: $U_{P95} = \pm 0{,}99 W$ for the electrical power, $U_{H95} = 0{,}108\, W/m^2$ for the heat flux, $U_{T95} = \pm 0{,}16\ °C$ for the temperature and $U_{u_{ref}95} = \pm 0{,}21\ m/s$ for the air velocity.

2.5. Experimental procedure

Sixteen different experiences of three days (72 hours) each were conducted. The time interval between two measurements was 10 minutes. One of the advantages of the reduced scale model is that it allows to easily change the size of the SC and to regulate both the intake air speed and the heaters capacity. The test conditions are identified in Table 2.1 together with the explanation of identification number of each case.

Table 2.1 - Summary of the test cases

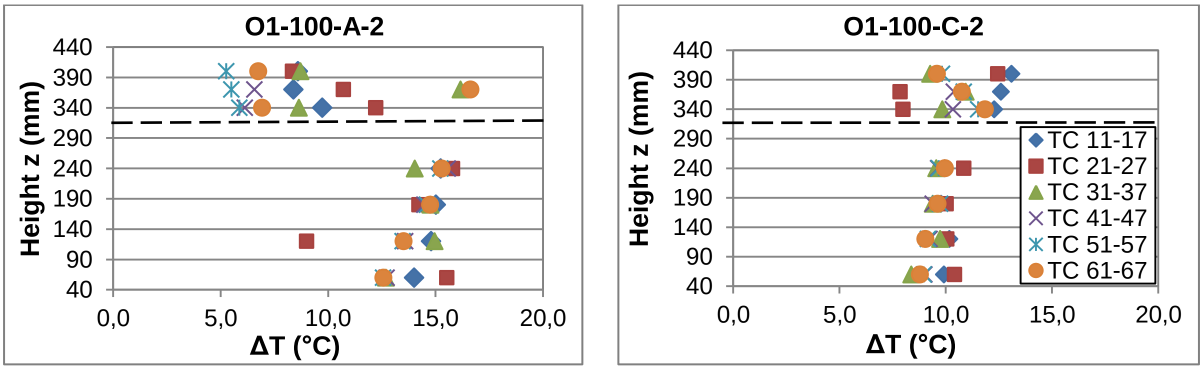
Case	Opening's placement	Heat load (W)	Gap	Mean velocity (m/s)	Re
O1-62-A-1	Above the SC	62	0%	1,1	5 807
O1-62-B-1	Above the SC	62	2,5% x 2,5%	1,1	5 807
O1-62-C-1	Above the SC	62	7,5% x 10%	1,1	5 807
O1-62-D-1	Above the SC	62	No SC	1,1	5 807
O1-100-A-1	Above the SC	100	0%	1,1	5 807
O1-100-B-1	Above the SC	100	2,5% x 2,5%	1,1	5 807
O1-100-C-1	Above the SC	100	7,5% x 10%	1,1	5 807
O1-100-D-1	Above the SC	100	No SC	1,1	5 807
O1-62-A-2	Above the SC	62	0%	2,05	10 800
O1-62-B-2	Above the SC	62	2,5% x 2,5%	2,05	10 800
O1-62-C-2	Above the SC	62	7,5% x 10%	2,05	10 800
O1-62-D-2	Above the SC	62	No SC	2,05	10 800
O1-100-A-2	Above the SC	100	0%	2,05	10 800
O1-100-B-2	Above the SC	100	2,5% x 2,5%	2,05	10 800
O1-100-C-2	Above the SC	100	7,5% x 10%	2,05	10 800
O1-100-D-2	Above the SC	100	No SC	2,05	10 800

The temperature of the laboratory fluctuates following the weather and the seasons. It is important to note that this variation of the temperature of the laboratory influences the temperature of the air in the reduced scale model. This problem was overcome by defining a temperature difference variable for each TC as $\Delta T = T_{TC} - T_{lab}$ where T_{TC} is the temperature measured by the thermocouple and T_{lab} the temperature of the laboratory. This solution allows to minimize the impact of the laboratory temperature variation, and to compare the temperatures between tests even with different experimental conditions, and made at different times of the year.

3. Results and discussion

To conduct the sixteen experiments, two mean air velocities ($1{,}1$ and $2{,}05\ m/s$), two heat loads (62 and $100\ W$), and four different configurations of SC (SC without gap, SC with 2,5% x 2.5% and 7,5% x 10% gaps, as well as no SC) have been employed.

Concerning the HP, the thermal plume is originated by the electrical resistance and entrains air around it. Then, it takes this warm air to the plenum, and diffuses it along the slab. Inside the plume, the temperature of the air decreases with the increasing of the height. The contrast between the use of the different SC configurations is that the complete SC induces a thermal stratification in the occupation zone only, see Figure 3.1 (a), while the SCs with gaps allow the warm air to pass through it, and engender the stack effect in all the reduced scale model, see Figure 3.1 (b).



(a) (b)

Figure 3.1 - Difference between the temperature of the air and the temperature of the laboratory from experiments with 100 W, and velocity 2, data retrieved the second day, 2 hours after the electrical resistance is switched on. The horizontal dashed line indicates the position of the SC. (a) Results with a complete SC. (b) Results with the widest peripheral gaps.

Consequently, the same observation as that of Lança et al. [22] is made: the peripheral gap of the SC allows the heat generated in the occupation zone to be partially used to heat up the plenum and the slab. Indeed, Figure 3.2 shows that the temperatures of the slab in the HP are higher when a gap is present (O1-100-B-1 and O1-100-C-1) than in the case of a complete SC (O1-100-A-1). As a result of the previous observation, the air temperature in the occupation zone during the HP is lower when the SC presents a peripheral gap with the side walls. This trend is visible in Figure 3.1 with the temperatures below the SC in case O1-100-A-2 higher than in case O1-100-C-2. The precedent observation is in line with the work of Domínguez et al. [14] because it was found that the smaller the gaps are, the lower the convective heat exchange between the occupation zone and the plenum is. This is identified as a cause in the reduction of the cooling performance. Also, the gap between the SC and the side walls attenuates the peak temperatures, in the reduced scale model of the office. As a matter of fact, in Figure 3.3, $\Delta\bar{T}_{HC}$ decreases significantly from $17{,}17\,°C$ without a gap to $12{,}61\,°C$ for the smallest gap.

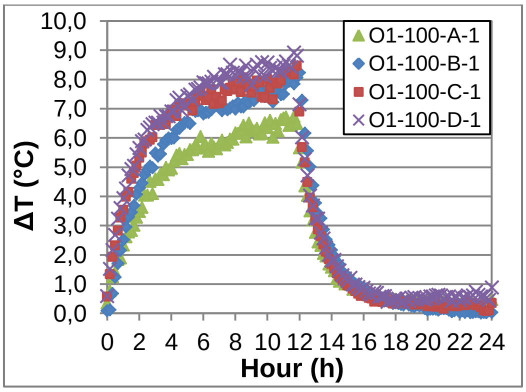


Figure 3.2 - Evolution of the difference between the temperature of the slab and the temperature of the laboratory for one thermocouple located at $x = L_x/2$ and $y = L_y/\,2$, and placed at the lower surface of the slab (S8), for the experiments conducted with $100W$ and velocity 1.

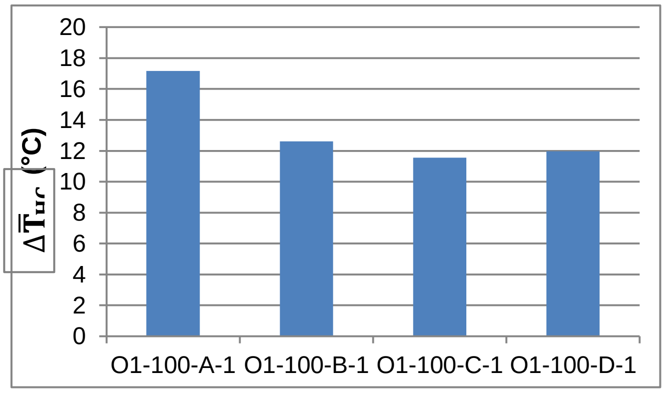


Figure 3.3 - $\Delta\bar{T}_{HC}$Difference between the average temperatures achieved at the end of the heating and cooling periods for thermocouple 64, results from the tests with $100W$ and velocity 1.

The latter observation is in agreement with the analysis of the heat flux results. During both the HP and the CP, the heat flux values obtained by the tests with the SC with gaps and without SC are higher than the ones coming from the test with a full SC, see Figure 3.4.

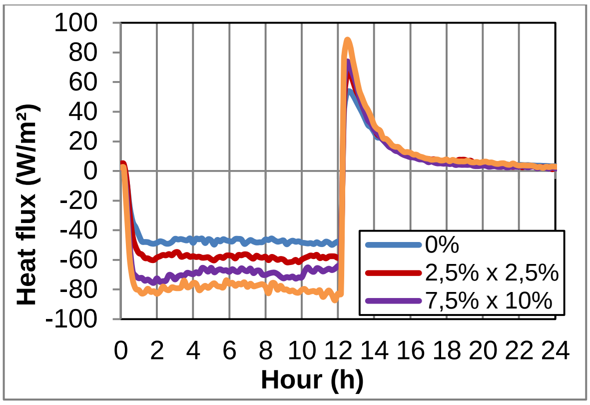
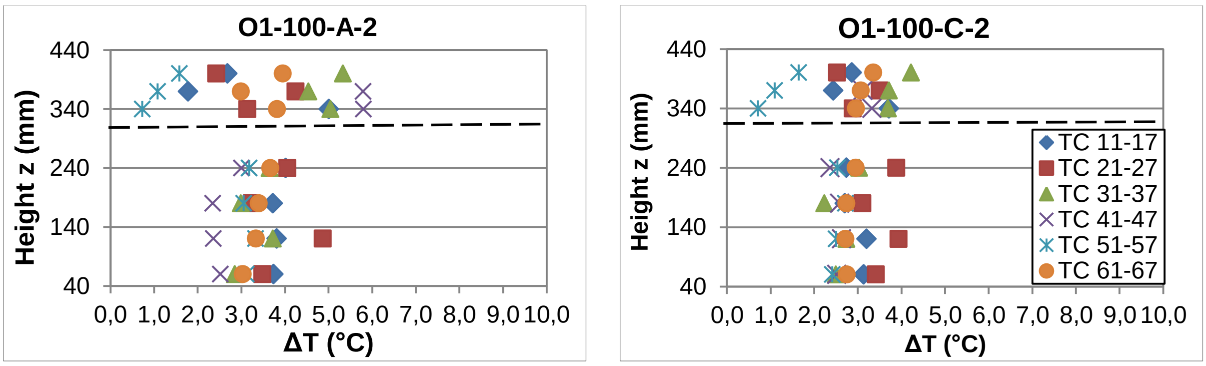


Figure 3.4 - Heat fluxes measured at ($x = 150mm$, $y = L_y/2$)for test cases with the 100W and velocity 1.

Furthermore, during the initial period of the CP, the air temperature above the SC is higher when there is no gap or there is a small gap, than when there is a large gap or no SC, see Figure 3.5 (a) and (b). Consequently, even though the air openings are placed above the SC, the cooling process is more efficient and homogenized when the SC has a peripheral gap. The incoming air flow passes through it and reaches all the zones of the model more easily. In addition, in all the tested configurations, the columns n°2 and 5, which are located at $x = L_x/2$, always cool faster in the plenum than in the occupation zone for all the tests. This means that the flow field of the incoming cool air is really concentrated in the upper centered part of the enclosure, even in the absence of SC.



(a) (b)

Figure 3.5 - Difference between the temperature of the air and the temperature of the laboratory at 30 minutes after the beginning of the CP for all the TCs of tests conducted with 100 W and velocity 2. The horizontal dashed line indicates the position of the SC. (a) Results with a complete SC. (b) Results with the widest gap.

Moreover, it can be acknowledge that the NV strategy is efficient in all of the sixteen cases because at the end of the CP the values of the ΔT values of the air temperatures, the slab temperatures (Figure 3.2) and the heat flux values (Figure 3.4) are close to 0 $°C$ or W/m^2. This means that the enclosure has the same temperature as the outside air. So, the thermal mass, which buffered the heat released in the model during the day, released all of it during the night.

3. Conclusion

Comparisons were made between the experimental results obtained by Lança et al. [22] and the ones of the present work, for the HP of 12 hours. Not only, there are no qualitative differences comparing the results of heat fluxes from the two works, and then the ones of temperatures, for the same test configurations, but also no significant quantitative differences. Indeed, the curves have the same trends and reach the same values. Because the results for the HP from the present work are coherent with the ones from Lança et al. [22], then the outcomes for the CP are considered reliable.

The efficiency of night cooling was tested. It was found that the slab core temperature drops by $6{,}5°C$ in only 6 hours of night cooling operation, for the case with the larger peripheral gap, the higher heat load, and the lower air velocity. This demonstrates how this technique is effective. Moreover, NV depends directly on heat load released by the electrical resistance during daytime, the air flow rate during the nighttime, and the size of the peripheral gaps, i.e., the CCR. The results indicate that the smaller the gaps are, the lower the convective heat exchange between the occupation zone and the plenum is. This is identified as a cause in the reduction of the cooling performance. As a result of the previous observation, wider gaps between the suspended ceiling and the walls contribute to involve the slab in the passive technique of cooling. The effectiveness of coupling NV and thermal mass is observed in indoor temperature profiles of the following day, with the attenuation of indoor peak temperatures.

It was also found that the areas closer to the supply and exhaust air openings cool down faster than the others in all the tested configurations. Consequently, even when there is no SC, the air flow is largely concentrated in the upper centered part of the reduced scale model, with higher velocities. However, it has been found that SCs with peripheral gaps induce a more homogenized cooling than the complete SC. Indeed, gaps between the SC and the side walls allow the air flow to reach all the zones of the reduced scale model.

To sum up, this thesis succeeded in better understanding the heating of the slab and the thermal plume characteristics during the HP, but also in apprehending the air flow fields during the CP.

As a consequence of all the previous conclusions, this work corroborates that NV technique is a solution to reduce the energy consumption of buildings, and more precisely the energy requirements of HVAC systems, while maintaining an acceptable indoor environment. Moreover, modern office buildings can be designed to be ventilated more efficiently with architectural elements, such as a SC with peripheral gaps. Indeed, it allows mixing between the air below and above it and so, enhances the cooling capacity.

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