# Bulk airflow measurements in a large naturally ventilated atrium in a mild climate


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## ABSTRACT

In recent years, concerns about global warming and greenhouse gas emissions have motivated designers to reduce building energy consumption through the implementation of passive solutions without compromising users' thermal comfort. This evidence has stimulated a renewed interest in designers for the exploitation of natural ventilation as means of passive cooling solutions. The adoption of ventilative cooling is particularly suitable for large spaces (non-residential buildings) as a measure to reduce the HVAC system high cooling loads. Due the inability to control and ensure a constant airflow rate through natural ventilation most of the times designers choice goes towards mixed-mode buildings. Mixed-mode buildings are designed in such a way that the HVAC system acts as backup to prevent uncomfortable conditions when natural ventilation is not sufficient to guarantee a comfortable environment. Unfortunately, information about the actual performance of mixed-mode buildings is difficult to obtain due the difficulties to set up measurements in naturally ventilated buildings that highly depend on building geometry and outdoor conditions (weather, pollution and noise). This limitation leads designers to follow a traditional design approach based on mechanical air conditioned systems.

With the aim of reducing the lack of information about the actual performance of mixed-mode non-residential buildings, this paper presents a full-scale bulk air flow measurements for a large naturally ventilated atrium in a mild climate. The methodology and the results presented in this paper refers at the first step of a more complete and complex work which aims at assessing the performance of the large mixed-mode atrium. The general performance of the atrium are tested through a long term measurement campaign which is indeed ongoing. The final aim is to quantify the effect of ventilative night cooling in term of cooling energy reduction and indoor thermal environment.



## KEYWORDS

Full-scale bulk airflow measurement, tracer gas technique, large naturally ventilated atrium

# 1 INTRODUCTION

In recent years, concerns about global warming and greenhouse gas emissions have motivated designers to reduce building energy consumption through the implementation of passive solutions without compromising users' thermal comfort. The continuous improvements of building thermal envelope properties combined with the increased level of internal gains changed the non-residential building energy balance. These effects led to a lower heating demand while raising the problem of increased cooling demand during the whole year. This evidence has stimulated a renewed interest in designers for the exploitation of natural ventilation as means of passive cooling solutions.

The presence of large open spaces, such as lobbies and atria, in non-residential buildings architecture helps the implementation of passive cooling solutions through natural ventilation strategies. Before the uptake of air conditioning, especially in Eastern countries, indeed, large open atria property of air stratification were used to remove warm air from top allowing colder air entering from lower level providing comfortable conditions (Kuppaswany I., 2015).

In the case of large spaces, the adoption of passive cooling systems is further justified by the higher users' tolerance to warmer thermal environment under summer conditions, as proved by (Chun C., 2004 ; Pitts A., 2008).

Nowadays, the practise of using natural ventilation for cooling purpose is named Ventilative cooling. The international research project Annex 62 of the International Energy Agency (IEA), (IEA EBC Annex 62, 2014-2017), focuses its research activity on solutions and design methods for ventilative cooling.

Due the inability to control and ensure a constant airflow rate through natural ventilation most of the times designers choice goes towards mixed-mode buildings. Mixed-mode buildings are indeed designed in such way that the HVAC system helps to prevent uncomfortable conditions when natural ventilation is not sufficient to guarantee a comfortable environment. Information about ventilation design strategies, controls and integration between natural ventilation and HVAC systems can be found in literature. For example, within the Annex 62 this typology of information for different case studies among Europe have been collected in a database. Information can be retrieved on the project webpage (Annex 62, 2014-2017).

Nevertheless, information about the actual performances of mixed-mode buildings is difficult to source. This lack of information is keeping designers and building owners to follow a traditional design based on reliable mechanical and air conditioned systems.

The lack of information is justified by the objective measurements difficulties of assessing the actual performance of naturally ventilated spaces. Full-scale investigation of ventilation performances are mostly assessed by traces gas techniques. When the size of the internal volume involved is greater than 5000 $m^3$ measurement difficulties becomes progressively more considerable (IEA EBC Annex 26, 1998).

Difficulties go from technical to economic aspects. Because of the big volume, reaching a perfect air/gas mixing is really challenging and large quantity of traceable gas and time for the experiment are required. Large spaces implicate the need of a high number of sensors to track the evolution of the conditions inside the space. It has also to be considered the variability of outdoor weather condition to which the observer has no control. The quantification of the bulk airflow rate is also a requirement when performing the validation of thermal simulation models (Mateus et al., 2016).

This paper presents the methodology and the results of full-scale bulk air flow measurements in the naturally ventilated atrium of a mix-mode multi-service building located in a mild climate. A first full-scale bulk airflow measurement is necessary in order to derive a correlation factor between the bulk air flow rate and the air velocity through the inlet windows. The correlation can be later used to quantify the airflow through openings at night measuring air velocity at inlet level during a long term measurements campaign.

The methodology and the results presented in this paper refers at the first step of a more complete and complex work which aims at assessing the performance of the large mixed-mode atrium. The general performance of the atrium are tested through a long term measurement campaign which is indeed ongoing. The final aim is to quantify the effect of ventilative night cooling in term of cooling energy reduction and indoor thermal environment.

## 2 CASE STUDY

The building is located in the mild climate of Seixal, in the south bay area of Lisbon, Portugal (see Figure 1). It is a multi-service building consisting of two main blocks with 3-floors connected by a central atrium. Each block is equipped with both single and open space offices. On its north –west orientation the building faces an Auditorium which is physically separated from the main building. The ground floor is occupied by the atrium and a cafeteria. In the basement there are a parking, the technical room and an archive. The two offices blocks face North and South orientation.

The central atrium (volume ≈ 16244 m$^{3}$) is a transitional space for temporary users and people working in the adjacent offices as well as a working area for internal employees. The space is conditioned by means of a radiative floor system, which is supported, during mid-season and summer, by a night-time ventilative cooling strategy. The nighttime ventilative cooling strategy involve different openings located at different oriented façades.


Figure 1 Building view from the outside (left), an internal view of the central atrium (middle) and night ventilation strategy (right)

Wind and stack-driven ventilation runs during night circulating airflows from West to East side of the atrium through top hung openings located at different heights. The strategy was designed considering the prevailing wind direction on the site which at night usually comes from the ocean, namely from North-West orientation.

On the inlet side (West façade) there are two row of windows consisting of 8 openable module each. On the outlet side (East façade) there is one row of 12 windows and just 5 of them can be operated. All the windows have two positions, totally closed or 25 º opening angle. No modulation is applied. Windows features are reported in Table 1.

Table 1 Features of the windows used in the ventilation strategy

| **Façade Orientation** | **Dimension** | **Typology** | **Maximum opening angle** | **Number of Module** | **Reference height of the middle plane from the ground** |
|---|---|---|---|---|---|
| West | 130 cm x 95 cm | Top hung tilted | 25º | 14 (7 mod/row) | 2.12 m (first row) 3.1 m (second row) |
| | 85 cm x 95 cm | Top hung tilted | 25º | 2 (1 mod/row) | 2.12 m (first row) 3.1 m (second row) |
| Est | 124 x 145 cm | Top-hung tilted | 25º | 5 | 13.8 m |

The windows are equipped with electric actuators which are connected to the general Building Management System (BMS) of the building. The control strategy is manual which means that the technical engineer of the building, based on outdoor and indoor climatic conditions, decides between two different modes. When mode A is selected, on inlet side only the second row of windows is opened while on outlet side 3 windows are operated. Under mode B, all openable windows on both inlet and outlet are operated. Information about the two modes are shown in Table 2.

Table 2 Control modes for windows operations

| **Mode** | **Inlet Openings** | **Outlet Openings** | **Opening Area [m$^2$]** | **Opening Area/Floor Area** |
|---|---|---|---|---|
| A | Second row | 3 modules | 9.7 | 1% |
| B | First & Second row | 5 modules | 18.7 | 2% |

When night ventilation is applied, the windows are kept opened for all night starting from closing hours till the morning after.
The ventilation strategy was tested by the technical engineer also during working hours. Because of complains about draught from the people working in the atrium, he decided to operate windows only at night.

## 3 METHODOLOGY

Full-scale measurements of airflow in buildings are commonly performed by using tracer gas technique. This technique is based on the injection of gas into the space which concentration response is then measured. Carbone dioxide was used as tracer and two different tracer gas methods were tested. The first method, *Constant release method*, consists in a continuous release of a traceable gas into the space with a constant flow during the entire measuring period. When stabilized indoor conditions are reached the bulk airflow can be calculated by solving the mass balance described in equation (1) (Mateus et al.,2016).

$$F\left(\frac{m^3}{h}\right) = \frac{CO_{2,released}\left(\frac{mg}{s}\right)}{[CO_{2,outlet}]-[CO_{2,inlet}]\left(\frac{mg}{m^3}\right)} * \frac{1}{3600} \quad (1)$$

After reaching stabilized indoor conditions the release of the $CO_2$ is stopped and a natural decay of its concentration begins. By knowing the $CO_2$ concentration at multiple point during the decay it is possible to calculate the airflow through the equation (2) (Cui et al.,2015).

$$F\left(\frac{m^3}{h}\right) = \frac{\left(\sum_{j=1}^{n} t_j\right) * \sum_{j=1}^{n} ln\left[C(t_j) - C_{bg}\right] - n * \sum_{j=1}^{n} \ln\left[C(t_j) - C_{bg}\right]}{n * \sum_{j=1}^{n} t_j^2 - \left(\sum_{j=1}^{n} t_j\right)^2} * V_{atrium} \quad (2)$$

The bulk air flow rate is calculated with both methods and then the average value is used to calculate the correlation constant *k* through equation (3).

$$k = \frac{F}{v_{air\_in}} \quad (3)$$

## 4 EXPERIMENTAL SET-UP

The experiment is conducted under control mode A (see Table 2). Figure 2 shows the measurement setup. The $CO_2$ injection took place at 3.1 m from ground, close to the inlet in two different positions. The air velocity of the air entering the atrium is monitored at the same level. A central row of $CO_2$ and air temperature sensors is used to track the development of the conditions (air temperature and $CO_2$ concentration) inside the atrium as well at the outlet level. Sensors characteristics are collected in Table 3.

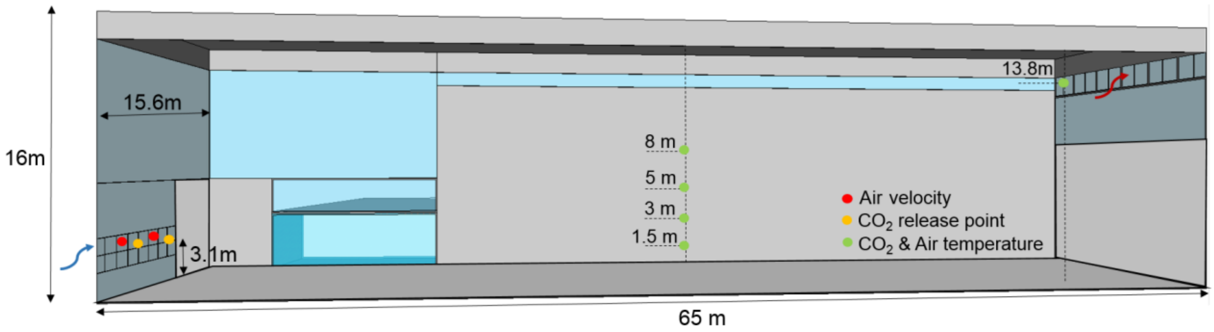


Figure 2 Location of the sensors used for the experiment and $CO_2$ release point location

Natural ventilation relies on natural forces. For this reason information about the actual climatic conditions of the building site are important for the assessment of the ventilation performance. Therefore a dedicated weather station was positioned close to the building in an open free area at 5 m above ground level. It consists of a wind speed and direction sensors, a pyranometer to measure global and diffuse radiation and a temperature and humidity sensor. The sensors specification are collected in Table 3.

The experiment was performed at the end of May 2017, after public opening hours, once the building was not occupied. Starting from 6:30 p.m. 2 $CO_2$ canisters released $CO_2$ in the atrium for two hours and a half before reaching stabilized conditions at around 9:15 p.m. During this time the $CO_2$ release rate was monitored in order to assure it was a constant rate. Once the stability was reached the release of $CO_2$ was stopped and a natural decay process started and lasted about 45 minutes. The experiment concluded at 22:00 p.m..

Table 3 Specification of the measurement equipment used

| **Sensor** | **Measurement** | **Specification** | |
|---|---|---|---|
| F900 S-P Airflow Sensor, ONSET | Air velocity ( indoor) | Range | 0.15 to 10 m/s |
| | | Accuracy | 10% ± 0.05 m/s |
| CO2 Meter (K-33 ELG) | Carbon dioxide ( indoor) | Range | 0-10000 ppm |
| | | Accuracy | ± 30 ppm + 3% |
| | Temperature( indoor) | Range | -40 to + 60°C |
| | | Accuracy | ±0.4 °C at 25 °C |
| Wind Monitor 05103 Campbell Scientific | Wind speed(outdoor) | Range | 0-100 m/s |
| | | Accuracy | ± 0.3 m/s or 1% reading |
| | Wind Direction(outdoor) | Range | 0 to 360 ° |
| | | Accuracy | ±3 ° |
| Pyranometer SPN1 Delta-T Devices | Solar radiation ( global and diffuse) | Range | 1 to 2000 $W/m^2$ |
| | | Accuracy | ±5% ±10 W/m2 |
| HOBO (U12-013) | Temperature (outdoor) | Range | −20.0 to 70.0 ◦C |
| | | Accuracy | ±0.35 ◦C from 0 to 50.0 ◦C |

## 5 EXPERIMENTAL RESULTS

Pressure differences drive the circulation of airflow within building. The pressure difference can be either generated by wind or by the thermal stratification inside the building, named buoyancy. Starting from the measured data, we first calculated the pressure differences due to wind and buoyancy, in order to understand the main driving forces during the experiment. The pressure force due to wind is calculated according to equation (4) while the one produced by buoyancy according to equation (5).The combined effect can be calculated with equation (6).

$$\Delta P_{,w} = \frac{1}{2}\Delta C_p \rho W_s^2 \qquad (4)$$

$$\Delta P_{,b} = \rho g (H_{out} - H_{in})\left(\frac{T_{out} - T_{outlet}}{T_{outlet} + 273.15}\right) \qquad (5)$$

$$\Delta P_{,tot} = \sqrt{\Delta P_{,w}^2 + \Delta P_{,b}^2} \qquad (6)$$

The pressure coefficient is the ratio of the local wind driven static pressure and the incoming wind pressure express by equation (7)

$$C_p = \frac{P_{local}}{\frac{1}{2}\rho U_{ref}^2} \qquad (7)$$

The pressure coefficient difference, $\Delta C_p$, used in equation (4), is the difference between the average pressure coefficient at inlet and the one at outlet calculated according to equation (7). By means of a CFD simulation model we calculated the local pressure, $P_{local}$, generated by the wind at inlet and outlet level for eight different wind orientations. The simulation have been run with the commercial CFD code Ansys Fluent 15 (Ansys, 2017) and the results are collected in Table 4.

Table 4 Pressure coefficient at inlet, outlet and difference

| | **N** | **NE** | **E** | **SE** | **S** | **SW** | **W** | **NW** |
|---|---|---|---|---|---|---|---|---|
| $Cp_{in}$ | -0.73 | -0.27 | -0.18 | -0.54 | 0.00 | 0.46 | 0.97 | 0.31 |
| $Cp_{out}$ | -0.64 | 0.07 | 0.19 | 0.33 | -0.58 | -0.72 | -0.42 | -0.82 |
| $\Delta C_p$ | -0.09 | -0.35 | -0.37 | -0.86 | 0.58 | 1.18 | 1.39 | 1.13 |

Minute by minute, depending on the wind direction we calculate the $\Delta P_{,w}$ by using the associated $\Delta C_p$. The analysis of the pressure trend during the experiment is essential to have a picture of the behaviour of the atrium during the whole experiment.
The graph in Figure 3 shows the distribution of the wind direction, the wind speed and the pressure generated by wind during the experiment. The prevailing wind direction was from north and north-west orientation. It is also observed a progressive decrease of the wind speed along the duration of the experiment. While the pressure due to wind decrease with time, the difference between indoor and outdoor temperature increase resulting in an increase buoyancy pressure (**Error! Reference source not found.**). For the first half of the experiment the main driving force is the wind pressure which is very variable and unstable as shown in Figure 5. In the second half, the airflow is mainly driven by the buoyancy resulting in more stabilized conditions.
With reference to the $CO_2$ concentration variation, three different phases during the experiment can be identified as showed in Figure 6.
The first phase is the *mixing phase*, where the total pressure conditions are unstable and the $CO_2$ concentration progressively increases. This phase lasts around one hour and a half until a stable concentration of $CO_2$ is reached. At this point we enter in the second phase, named *stabilized phase*, where we observe stable conditions for both the $CO_2$ concentration and the total pressure for around one hour inside the atrium. The stabilized conditions allow us to calculate the average airflow. Considering a total $CO_2$ release of 1720 mg/s and a $CO_2$

concentration difference between inlet and outlet of around 330 ppm (600 mg/m$^3$), the airflow calculated through equation (1) is equal to 10306 m$^3$/h.
For both calculations the $CO_{2,inlet}$ and the $C_{bg}$ are equal and assumed to 400 ppm, measured value of the outdoor $CO_2$ concentration.

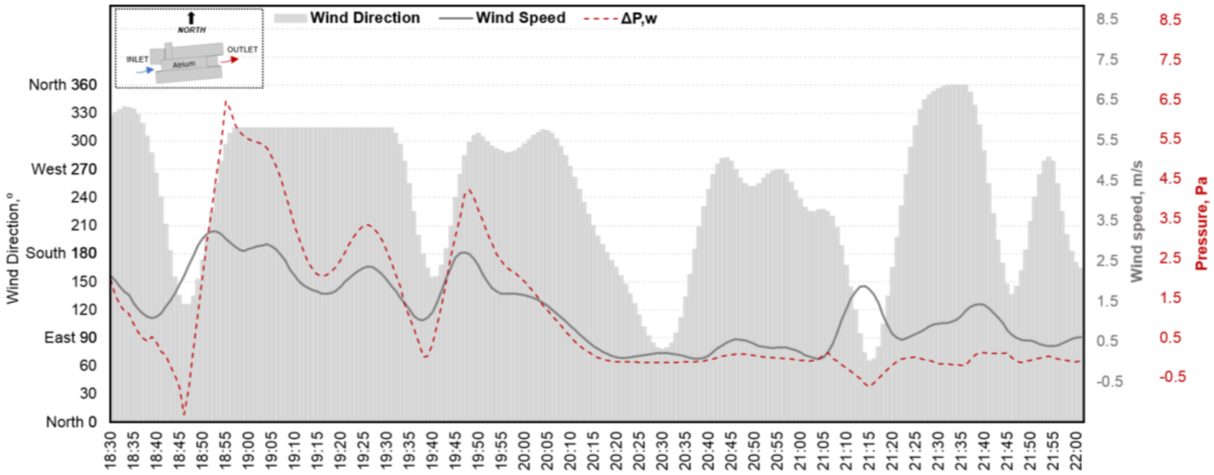


Figure 3 Wind distribution, wind speed and pressure generated by the wind

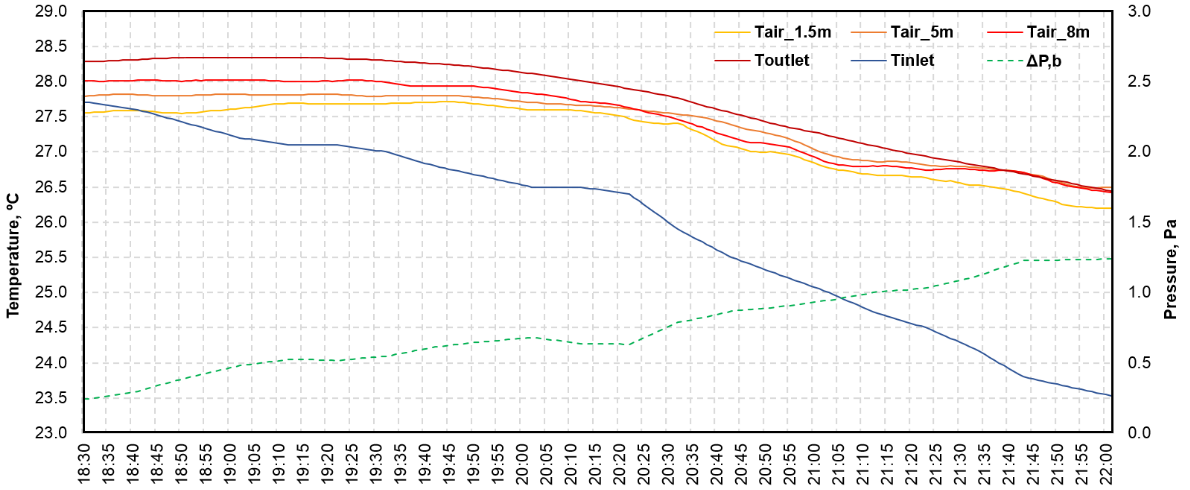


Figure 4 Temperature distribution during the experiment and buoyancy pressure

The last phase, named *decay phase*, starts when the $CO_2$ release is stopped and the $CO_2$ indoor concentration begins its natural decay. During this last phase we also observe stabilized condition of total pressure. The decay time was about 35 minutes until the initial conditions inside the atrium were reached again. The airflow calculated during the decay, through equation (2), it is equal to 9668 m$^3$/h .The error between the two methods is 6%. For the calculation of the constant correlation k we use the average of the two airflow values which is equal to 9987 m$^3$/h.
Considering an average air velocity at inlet of 0.36 m/s for the stabilized phase, the velocity constant, calculated though equation (3), is equal to 7.62.

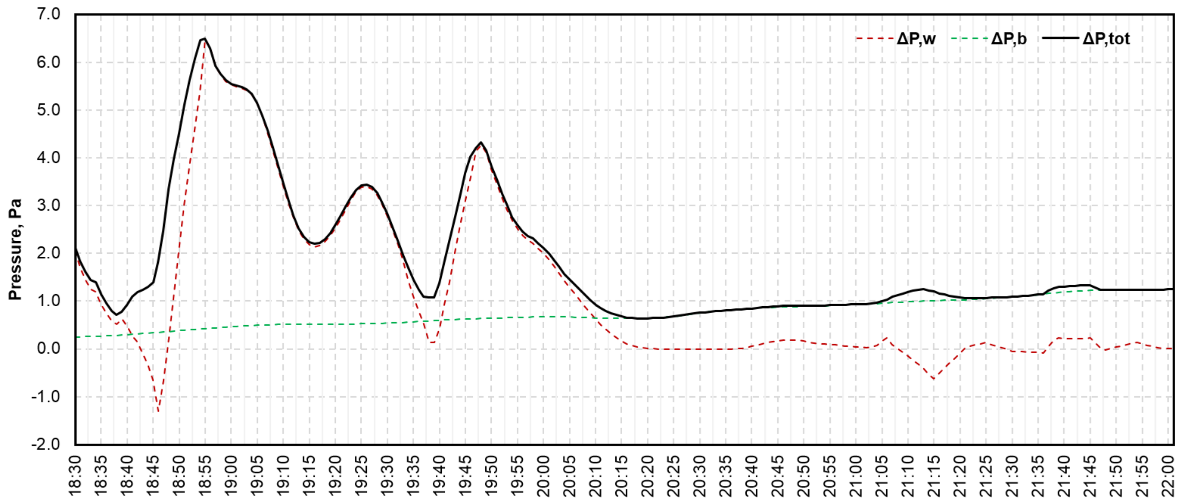


Figure 5 Physics of the pressure during the experiment

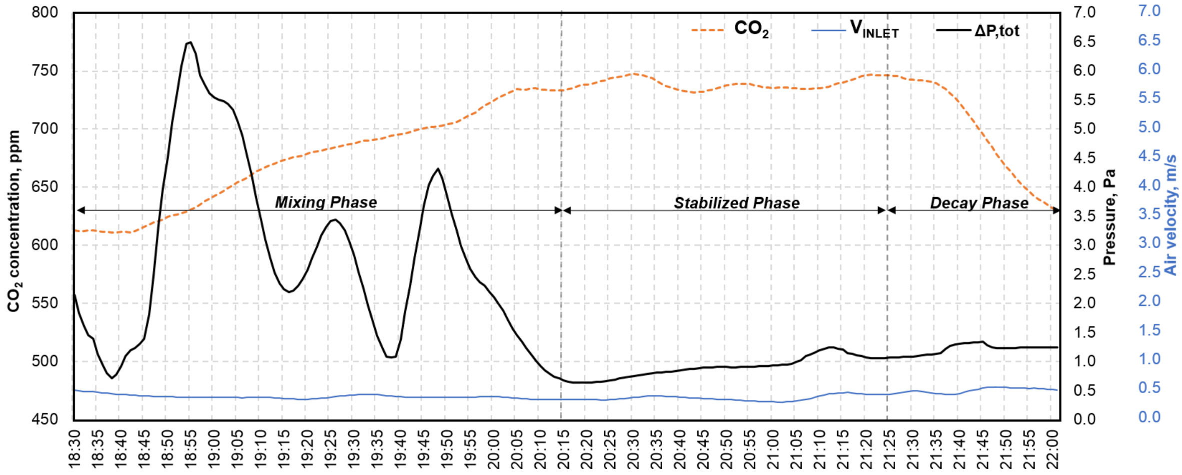


Figure 6 Phase of the experiment on the bases of $CO_2$ distribution

## 6 CONCLUSIONS

This paper presents the results of a full-scale bulk airflow measurements in a large atrium naturally ventilated. This measurement is the first step of a more complete research work .The finale objective is to quantify the effect of a wind and stack-driven night ventilation over the total cooling consumption of the radiant floor cooling system and the resulted indoor thermal environment of a large atrium. This quantification is possible through a long term measurements campaign comparing the performance with and without the use of the night ventilation.

In order to calculate the bulk airflow, two different tracer gas techniques were used during the experiment. A constant release technique followed by a natural decay. The tracer gas used is Carbon dioxide. The error in the bulk air flow prediction between the two methods is less than 10% and the average value is equal to 9987 $m^3$/h. An effective opening area of 9.7 $m^2$ with a temperature difference between indoor and outdoor of about 2 K, have generated during the experiment an average airflow of 0.61 vol/h.

The average value was used for the definition of a correlation constant between the average bulk air flow and the average air velocity of the air at inlet level. This correlation constant characterized the openings behaviour and it can be used to calculate the airflow rates during the long term measurement just tracking the air velocity at inlet level.

The work has shown the possibility of the application of tracer gas techniques also for large volume where the difficulties of application are wider.

The analysis of the pressure conditions during the experiment was a useful tool to understand whether or not stable condition were favourable for the direct calculation of the airflow rate.

## 7 NOMENCLATURE

F airflow rate [m$^3$/s]

$CO_{2,inlet}$ Carbon dioxide concentration at inlet level which equal to the $C_{bg}$ [mg/m$^3$]

$CO_{2,outlet}$ Carbon dioxide concentration measured at outlet level[mg/m$^3$]

$CO_{2,released}$ Carbon dioxide released during the experiment [mg/s]

n number of measurements points considered during the decay

$t_j$ j-th elapsed time from the decay process starting $t_1 = 0$

$C(t_j)$ measured gas concentration at time ($t_j$)

$C_{bg}$ background tracer gas concentration which is the outdoor concentration of Carbon dioxide [ppm]

$V_{atrium}$ volume of the atrium [m$^3$]

$\nu_{air\_in}$ average air velocity at inlet openings [m/s]

k correlation constant between average airflow rate and $\nu_{air\_in}$

$P_{local}$ local pressure generated by wind on a building façade

$Cp_{in}$ pressure coefficient at inlet

$Cp_{out}$ pressure coefficient at outlet

$\Delta Cp$ difference between the pressure coefficient at inlet and outlet

ρ air density [kg/m$^3$]

g gravitational acceleration [m$^2$/s]

$W_s$ wind speed [m/s]

$W_d$ wind direction [º]

$U_{ref}$ wind speed reference at weather station level (5m above the ground) [m/s]

$H_{inlet}$ distance between the middle plane of inlet windows and the floor

$H_{outlet}$ distance between the middle plane of outlet windows and the floor

$T_{out}$ outdoor temperature [ºC]

$T_{air\_1.5m}$ temperature measured at 1.5 meters from the floor [ºC]

$T_{air\_5m}$ temperature measured at 5 meters from the floor [ºC]

$T_{air\_8m}$ temperature measured at 8 meters from the floor [ºC]

$T_{outlet}$ temperature measured at 13.8 meters from the floor [ºC]

$T_{inlet}$ temperature at inlet level which correspond to the $T_{out}$ [ºC]

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