# COMPARISON OF DISPLACEMENT VENTILATION AND MIXING VENTILATION SYSTEMS WITH REGARD TO VENTILATION EFFECTIVENESS IN OFFICES

Michele De Carli*[1], Roberta Tomasi[1,] Roberto Zecchin[1], Giacomo Villi[1]

*1 Department of Industrial Engineering*
*Via Venezia 1, 35131*
*Padova, Italy*

**Corresponding author: michele.decarli@unipd.it*

## ABSTRACT

Air quality in offices depends on the ventilation system ability to remove contaminants from the occupied zone. In a low polluted building air quality mainly depends on the human presence and carbon dioxide is normally used as indicator of human bioeffluents.
The aim of this paper is to investigate, by using computational fluid dynamics (CFD) methods, the effect of the supply and exhaust positions on the contaminant distributions in an office equipped with a ceiling cooling system. Mixing ventilation was compared with different displacement ventilation solutions, adopting either floor or wall mounted displacement diffusers. Exhaust vents in the mixing ventilation cases were placed directly under the supply or on the opposite wall; in the displacement ventilation cases, exhaust vents were placed on the upper part of a sidewall or on the ceiling in different positions. Besides the percentage of dissatisfied PD [%] and the contaminant removal effectiveness, a discomfort index for the whole office was introduced and calculated. It resulted that, for the considered scenario, displacement ventilation performance was very sensitive to the position of exhaust grilles; moreover, it was found that displacement ventilation does not result always in better air quality than mixing ventilation.

## KEYWORDS

Computational fluid dynamics, contaminants, ventilation effectiveness, mixing ventilation, displacement ventilation, office.

## INTRODUCTION

Computational fluid dynamics represents an appropriate instrument for the prediction of contaminant distribution in offices, where the indoor air quality is important for both the health and productivity. Wargocki et al. [1] estimated that performance of office work increases on average by 1.5 % for every 10 % decrease in the percentage of persons dissatisfied with the air quality; they also studied the effects of pollution loads and outdoor air supply rates on Sick Building Syndrome (SBS) symptoms in office [2].
Within an office air quality is affected particularly by human presence. The occupants emit bioeffluents like carbon dioxide, carbon monoxide and water vapor in quantities variable with metabolic activity and age, as reported in [3] and [4]. Carbon dioxide is considered a good indicator of air quality in rooms with human presence even if it does not represent a serious

health problem at concentrations that generally occur indoor. Furthermore it was found that carbon dioxide concentration is connected to the acceptability of the space in terms of body odor (Persily, [5]). European Standard EN 15251 [6] recommends ventilation rates values in non residential buildings should be based on occupant density (to take into account the pollution emitted from persons) and floor area (to take into account the pollution emitted from building materials) basing on three indoor climate categories. In order to analyze the effectiveness of a ventilation system, the contaminant removal effectiveness index ($\varepsilon^c$) defined by REHVA [7] is meant to compare the concentration at the exhaust with the concentration in the room. CFD made it possible to calculate the contaminant removal effectiveness index in rooms equipped with different ventilation systems and to make comparisons between them. In the prediction of room airflow, the turbulence model plays an important role with respect to the accuracy of prediction and the required simulation time. It was demonstrated by Zhai et al.[8] that, among different turbulence models, the LES model was able to capture very detailed flow features for natural convection, forced and mixed convection, although computational time could take very long. The effect of the air supply location on the performance of a displacement ventilation system in a large office was investigated by Lin et al. [9], while Novoselac et al.[10] studied the vertical concentration of active pollutant sources ($CO_2$) and VOC from carpet in a conference room with a cooled ceiling combined with displacement ventilation.

In this work the carbon dioxide concentration was calculated in an office for three persons equipped with a ceiling cooling system and mechanical ventilation. Mixing ventilation was compared with different displacement ventilation strategies and the effects of both supply and exhaust locations were investigated.

## METHOD

An office room for three persons, equipped with mechanical ventilation combined to ceiling cooling was analyzed under typical summer conditions by means of CFD in order to analyze the effect of different ventilation systems on the resulting ventilation effectiveness which was quantified by the contaminant removal effectiveness index. Numeric simulations were performed be means of the FDS (Fire Dynamics Simulator) model which solves a modified form of the Navier-Stokes equations appropriate for low-speed thermally-driven flow; all spatial derivatives in the conservation equations are discretized by second order finite difference scheme and all the thermodynamic variables are updated in time by means of an explicit second order predictor-corrector scheme (McGrattan et al. [11]). Sub-grid modelling is performed by means of the Smagorinsky model which is based on the eddy viscosity assumption. FDS is characterized by fast computational speed and relatively modest requirements in terms of computational resources but is restricted to regular geometries. Although it has been developed for addressing fire related problems, the low Mach number assumption is also appropriate to describe building ventilation scenarios which do not include fires (McGrattan et al.[11]). Different examples of how the model can be used to investigate indoor airflow scenarios can be found in (Musser et al.[12]), (Lin et al.[13]), (Cho and Liu.[14]) and (Farnham et al.[15]).

The investigated office has dimensions 7 m (x dimension) × 4 m (z dimension) × 3 m (y dimension,(Figure 1) and the total internal heat gain considered is 680 W (3 persons and 3 computers). The ceiling surface temperature is supposed to be at 22°C while the floor and all the vertical walls are at 26°C. As occupants were considered sitting at their desk, the maximum height of the modeled person is 1.1 m corresponding to the head level according to ISO 7726 [16]. It was supposed that each person emits 0.02 $m^3$/h of carbon dioxide (which is the recommended value for an adult in sitting position [4]) and the contaminant source was

described as a rectangular patch (0.2 m × 0.1 m) positioned on the upper part of block representing the occupant body.
The office is ventilated with an outdoor air change rate of 1.5 $h^{-1}$ at 20°C of temperature. The ventilation rate was calculated assuming a 7 l/s ventilation rate per occupant and a 0.5 l/s$m^2$ ventilation rate for emissions from building materials. Different ventilation strategies were considered:

- Wall mounted diffusers (mixing ventilation: case 1 and 2);
- Floor mounted displacement ventilation inlets with radial, horizontal jet (case 3, 4 and 6);
- Floor mounted displacement ventilation diffusers with inclined discharge (case 5);
- A wall mounted displacement ventilation diffuser (case 7, 8, 9 and 10).

As to the exhaust, different (in size and location) outlets were adopted. Exhausts were placed on one of the two short side walls, at different heights, or on the ceiling, along the room's longitudinal axis. The ten cases considered in this work can be categorized as a function of the type, the number and the position of inlets and outlets as reported in Table 1 and shown in Figure 1.
Carbon dioxide concentration was calculated in 23 points considered relevant (taking into account the possible position of a generic occupant) for comfort (listed in Table 2), as shown in Figure 2. They are:

- In front of the occupants, at 1.1 m height, 20 cm from the table; this zone is reference to as "Table" and includes 3 points;
- Next to the desks, 80 cm far away and at 1.7 m height. This zone is referenced to as "Perimeter" and includes 4 points;
- In room's corners at 1.7 m height. This zone is referenced to as "Corner" and includes 4 points;
- Close to the desks, at 1.1m and 1.7 m. This zone is referenced to as "Desk1", Desk 2" and "Desk3" and 4 points are considered for each desk.

| | **Unit** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** | **Case 9** | **Case10** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Code** | | **MIX-1** | **MIX-2** | **UFAD-1** | **UFAD-2** | **UFAD-3** | **UFAD-4** | **DV-1** | **DV-2** | **DV-3** | **DV-4** |
| Total Internal heat loads | W | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 |
| Wall and floor surface temperature | °C | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| Ceiling surface temperature | °C | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 |
| Primary air inlet temperature | °C | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| Inlet air velocity | m/s | 0.29 | 0.29 | 0.22 | 0.22 | 0.22 | 0.22 | 0.18 | 0.18 | 0.18 | 0.18 |
| Primary air volume flow | $h^{-1}$ | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |

Table 1. Simulated configurations scheme.

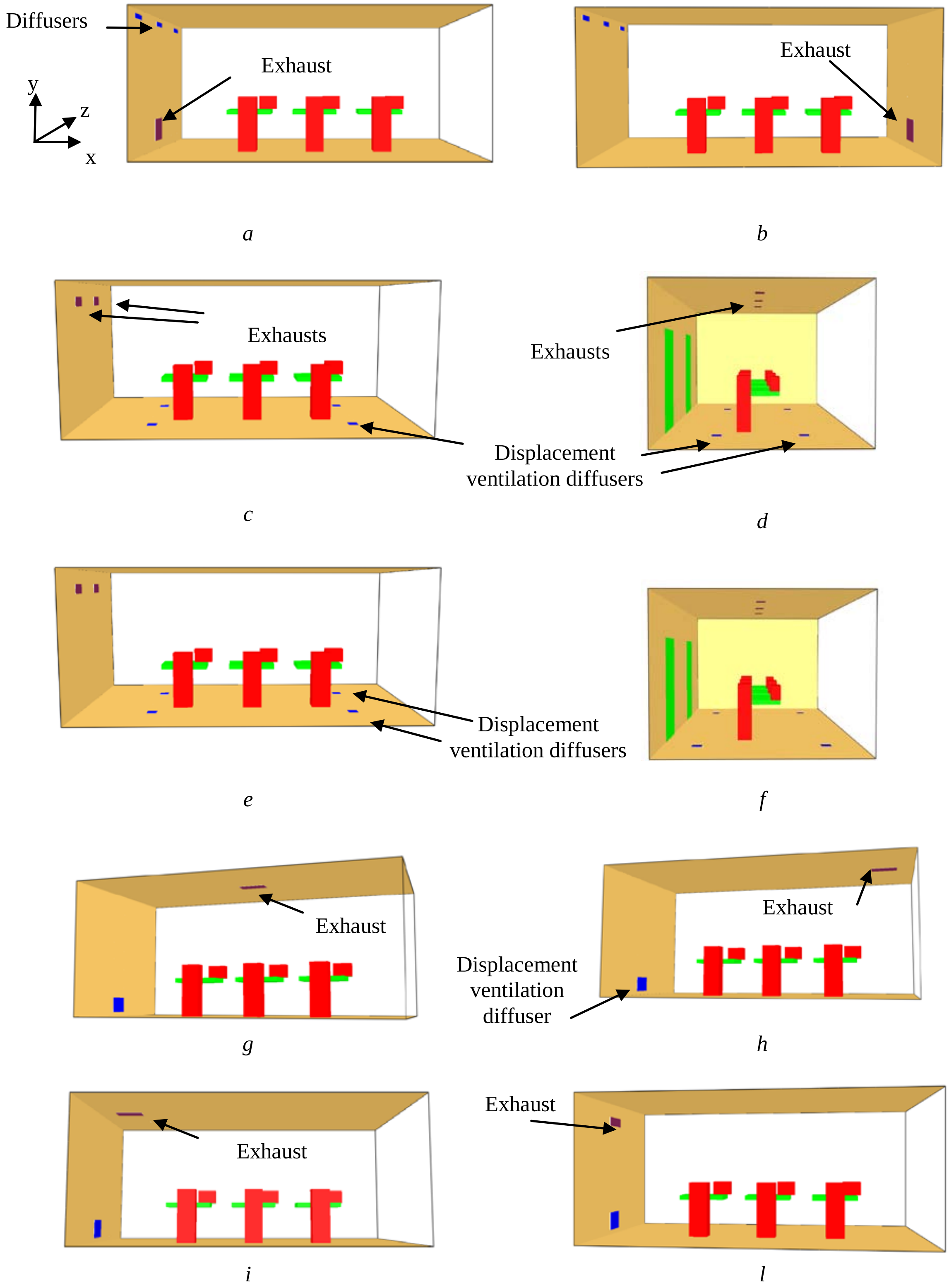


Figure 1 Layout of the simulated office for the different investigated cases: inlet air vent (blue) and outlet air vents (violet) for case 1 (a), case 2 (b), case 3 (c), case 4 (d), case 5(e), case 6 (f), case 7 (g), case 8 (h), case 9 (i) and case 10 (l).

| point n° | Zone | x [m] | z [m] | y [m] |
|---|---|---|---|---|
| 1 | Table 1 | 2 | 2 | 1.1 |
| 2 | Table 2 | 3.5 | 2 | 1.1 |
| 3 | Table 3 | 5 | 2 | 1.1 |
| 4 | Perimeter | 2.8 | 0.8 | 1.7 |
| 5 | | 4.3 | 0.8 | 1.7 |
| 6 | | 2.8 | 3.2 | 1.7 |
| 7 | | 4.3 | 3.2 | 1.7 |
| 8 | Corners | 1 | 0.5 | 1.7 |
| 9 | | 1 | 3.5 | 1.7 |
| 10 | | 6 | 0.5 | 1.7 |
| 11 | | 6 | 3.5 | 1.7 |
| 12 | Desk 1 | 1.7 | 1.3 | 1.1 |
| 13 | | 1.7 | 1.3 | 1.7 |
| 14 | | 1.7 | 2.5 | 1.1 |
| 15 | | 1.7 | 2.5 | 1.7 |
| 16 | Desk 2 | 3.2 | 1.3 | 1.1 |
| 17 | | 3.2 | 1.3 | 1.7 |
| 18 | | 3.2 | 2.5 | 1.1 |
| 19 | | 3.2 | 2.5 | 1.7 |
| 20 | Desk 3 | 4.7 | 1.3 | 1.1 |
| 21 | | 4.7 | 1.3 | 1.7 |
| 22 | | 4.7 | 2.5 | 1.1 |
| 23 | | 4.7 | 2.5 | 1.7 |

Table 2. Cartesian Coordinates of the 23 points in which carbon dioxide was calculated.

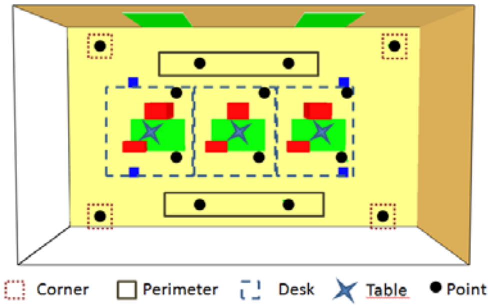


Figure 2. Assumed zones in the office, layout of case 4.

| Zone | N° points | Weighting coefficient ($c_i$) |
|---|---|---|
| Table | 3 | 10 |
| Perimeter | 4 | 5 |
| Corner | 4 | 3 |
| Desk 1,Desk 2, Desk 3 | 4 | 10 |

Table 3. Weighting coefficient $c_i$ for the different sampling points as a function of the macro zones the analyzed office was divided in.

Carbon dioxide is an indicator of human bioeffluents and, if occupants are the exclusive pollution source in a space, it is possible to determine the percentage of persons dissatisfied PD [%] with the level of perceived air quality by using the ASTM D6245:98 [17] equation:

$$PD\% = 392 \cdot e^{(-15.5 \cdot dCO_2^{(-0.25)})} \tag{1}$$

where $dCO_2$ is the difference between the outdoor and the indoor concentration. In the present analysis, it was assumed that the outdoor $CO_2$ concentration is zero, so that the calculated indoor concentration was used for the $dCO_2$ term.
In order to better compare the ten cases, a discomfort index ID [%] was introduced as the weighted value of the predicted percentages of persons dissatisfied PD [%] in a representative number of points in the room; the weighting coefficient (Equation (2)) is based on the relevance of the zone with respect to occupants.

$$ID\% = \frac{\sum_{23} (c_i \cdot PD\%)}{\sum c_i} \tag{2}$$

In the present case, the proposed parameter was applied to 23 sampling points which were conveniently distributed in the room, varying the weighting coefficients from 3 to 10 (e.g. the highest value, 10, is for the sampling points closest to the tables (Table 3) occupants are seated at). Finally, the contaminant removal effectiveness was calculated according to the REHVA method [7] where the adopted parameter ($\varepsilon^c$) is defined (Equation (3)) as the ratio between the contaminant concentration at the exhaust ($c_e$) and the contaminant concentration in the room $<c>$ to express how quickly an airborne contaminant is removed from the room. For all the investigated cases, $<c>$ was assumed to be the average of the $CO_2$ concentrations in the different zones of the office was divided in (i.e. “Perimeter”, “Desk1”…) while the concentration at the exhaust (i.e. $c_e$) was assumed to be the steady state concentration under the well mixed hypothesis and calculated according to Standard ASTM D6245-98 [17].

$$\varepsilon^c = \frac{c_e}{<c>} \tag{3}$$

## RESULTS

Results show that $CO_2$ equilibrium concentrations in the room were quite different depending on the adopted ventilation strategy. Figure 3 reports the calculated carbon dioxide concentrations at 1.1 m height for three different cases (i.e. mixing ventilation and two strategies for displacement ventilation). It is evident that mixing ventilation resulted in concentrations in all the volume (calculated concentrations are about 800 ppm for the case 1 simulation (Figure 3 a); as to the “case 2” scenario results were similar, (see Table 4)).
When displacement ventilation from floor is adopted (i.e. “UFAD” cases, Table 4) with exhaust on a wall (Figure 3 b), $CO_2$ concentrations resulted locally much higher than those resulting from the two mixing ventilation cases; as reported in Table 4, $CO_2$ concentration at Desk 1 (which is the closest to the exhaust) is higher than 1000 ppm in case 3 and case 5 and it decreased as the centre of the room is considered. In particular, it was found that case 3 and 5 presented the highest percentages of dissatisfied persons PD [%] and discomfort index ID [%], as shown in Tables 5 and 6. A significant improvement on air quality resulted from placing the exhaust on the ceiling with the same supply location: in the case three exhaust

outlets were placed on the ceiling, the average $CO_2$ calculated concentration is about 550 ppm (Table 4, Case 4) and the resulting discomfort index ID [%] decreased to 17.1% (Table 6). If the floor diffusers were placed far away from the desks (i.e. case 6) the average $CO_2$ was about 800 ppm and the discomfort index ID [%] was 22.5% even in the case the exhaust is placed on the ceiling.
Finally if displacement ventilation from wall mounted diffusers is considered (i.e. "DV" cases) the discomfort index ID [%] decreased to about 20%, regardless of the exhaust position (Table 6). Case 7, with the exhaust in central position, resulted in the lower $CO_2$ concentrations and Case 10 results, where the exhaust was placed just above the wall mounted displacement diffusers, are not so different from the previous DV cases: the discomfort index ID [%] is 20.1% (Table 6).
Similar considerations apply for the contaminant removal effectiveness: it was found that, excluding the table zone, the highest values resulted for Case 4 ($\varepsilon^c$ >0.9 for all the room's volume) followed by cases 7, 8, 9 and 10 ($\varepsilon^c$ >0.7), as shown in Figure 4 and Table 7.

| N° case | Case | Zone | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Table** | **Perimeter** | **Corner** | **Desk1** | **Desk2** | **Desk3** |
| **1** | **Mix 1** | 895.9 | 792.4 | 784.7 | 798.9 | 789.6 | 784.6 |
| **2** | **Mix 2** | 905.9 | 842.7 | 818.3 | 821.7 | 831.5 | 826.7 |
| **3** | **UFAD-1** | 1015.3 | 883.9 | 896.8 | 1018.9 | 911.6 | 801.7 |
| **4** | **UFAD-2** | 616.4 | 533.0 | 539.4 | 535.9 | 526.4 | 513.3 |
| **5** | **UFAD-3** | 1032.4 | 873.5 | 896.2 | 1024.8 | 907.4 | 791.8 |
| **6** | **UFAD-4** | 857.8 | 771.9 | 785.3 | 803.6 | 762.4 | 736.7 |
| **7** | **DV-1** | 804.3 | 673.9 | 663.3 | 656.2 | 670.8 | 656.7 |
| **8** | **DV-2** | 810.5 | 694.4 | 699.0 | 683.2 | 686.2 | 680.5 |
| **9** | **DV-3** | 850.3 | 715.7 | 726.6 | 729.0 | 720.3 | 682.3 |
| **10** | **DV-4** | 797.9 | 656.7 | 657.2 | 663.4 | 652.1 | 627.2 |

Table 4. Calculated average carbon dioxide concentration above outside air for each zone [ppm].

| N° case | Case | Zone | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Table** | **Perimeter** | **Corner** | **Desk1** | **Desk2** | **Desk3** |
| **1** | **Mix 1** | 24.6 | 22.7 | 22.6 | 22.9 | 22.7 | 22.6 |
| **2** | **Mix 2** | 24.9 | 23.7 | 23.2 | 23.3 | 23.5 | 23.4 |
| **3** | **UFAD-1** | 26.8 | 24.5 | 24.8 | 27.0 | 25.0 | 22.9 |
| **4** | **UFAD-2** | 18.7 | 16.9 | 17.0 | 16.9 | 16.7 | 16.4 |
| **5** | **UFAD-3** | 27.1 | 24.3 | 24.7 | 27.1 | 25.0 | 22.7 |
| **6** | **UFAD-4** | 23.9 | 22.3 | 22.6 | 22.9 | 22.1 | 21.5 |
| **7** | **DV-1** | 22.7 | 20.2 | 19.9 | 19.8 | 20.1 | 19.8 |
| **8** | **DV-2** | 22.9 | 20.6 | 20.7 | 20.4 | 20.5 | 20.3 |
| **9** | **DV-3** | 23.7 | 21.1 | 21.3 | 21.4 | 21.2 | 20.4 |
| **10** | **DV-4** | 22.6 | 19.8 | 19.8 | 20.0 | 19.7 | 19.1 |

Table 5. Percentage of persons dissatisfied PD [%] due to the calculated values of $CO_2$ concentration.

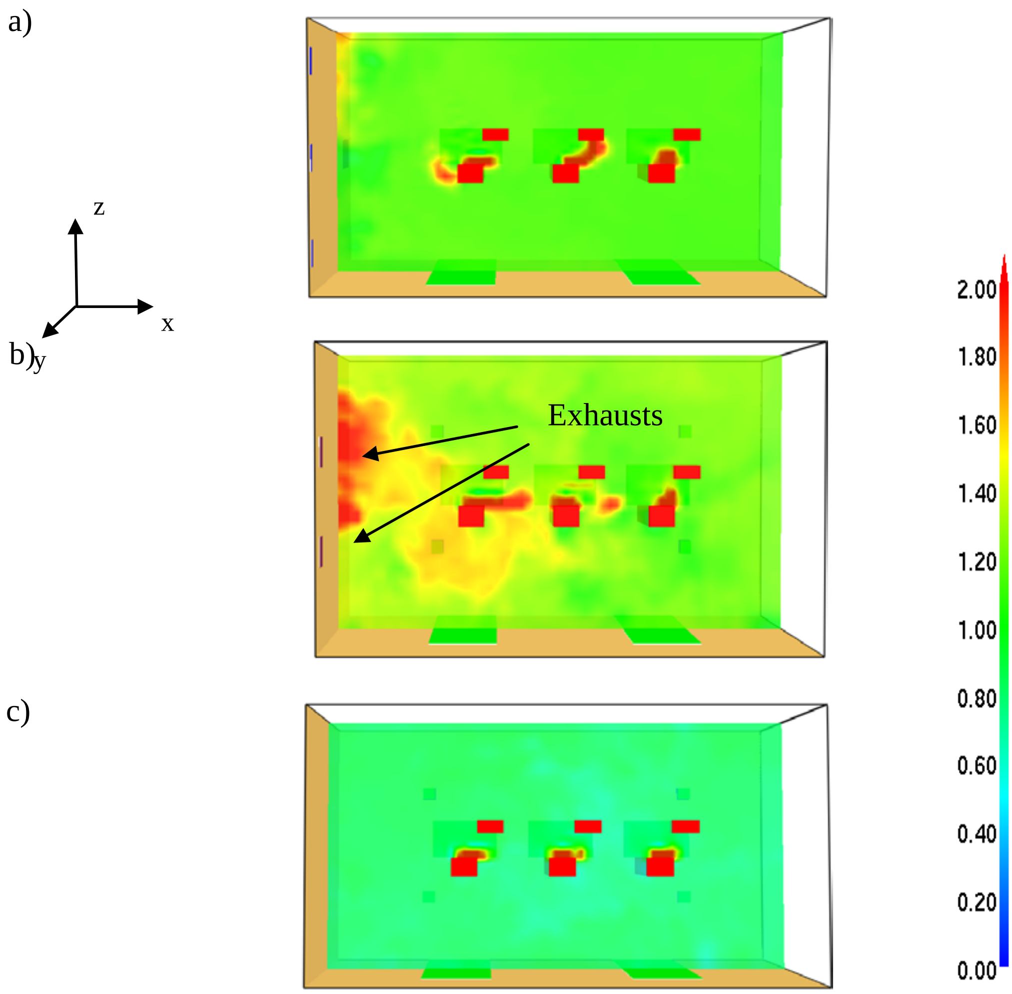


Figure 3. $CO_2$ distribution at 1.1 m height, at equilibrium, for case 1 with mixing air flow(a), cases 3(b) and case 4 (c) with displacement ventilation. Concentrations are expressed in [kg/kg $\times 10^{-3}$].

| **N° case** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Case** | **Mix 1** | **Mix 2** | **UFAD-1** | **UFAD-2** | **UFAD-3** | **UFAD-4** | **DV-1** | **DV-2** | **DV-3** | **DV-4** |
| **Discomfort Index [%]** | 23 | 23.7 | 25.2 | 17.1 | 25.2 | 22.5 | 20.4 | 20.9 | 21.5 | 20.1 |

Table 6. Discomfort index ID [%] for each case.

| N° case | Case | Zone | | | | | |
|---|---|---|---|---|---|---|---|
| | | Table | Perimeter | Corner | Desk1 | Desk2 | Desk3 |
| **1** | **Mix 1** | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| **2** | **Mix 2** | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| **3** | **UFAD-1** | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 |
| **4** | **UFAD-2** | 0.8 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| **5** | **UFAD-3** | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 |
| **6** | **UFAD-4** | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| **7** | **DV-1** | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| **8** | **DV-2** | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| **9** | **DV-3** | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| **10** | **DV-4** | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 |

Table 7. Contaminant removal effectiveness $\varepsilon^c$ [-] for all the analyzed cases and in different zones [-].

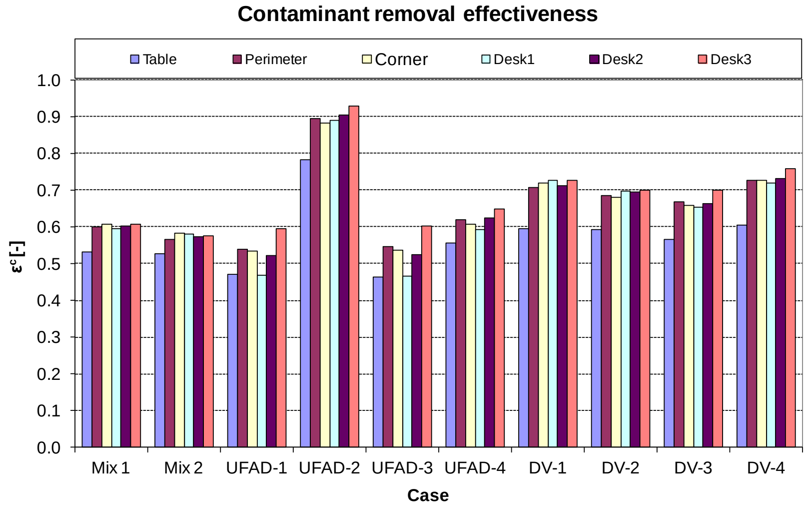


Figure 4. Contaminant removal effectiveness $\varepsilon^c$ [-] for different zones and for all the analyzed cases.

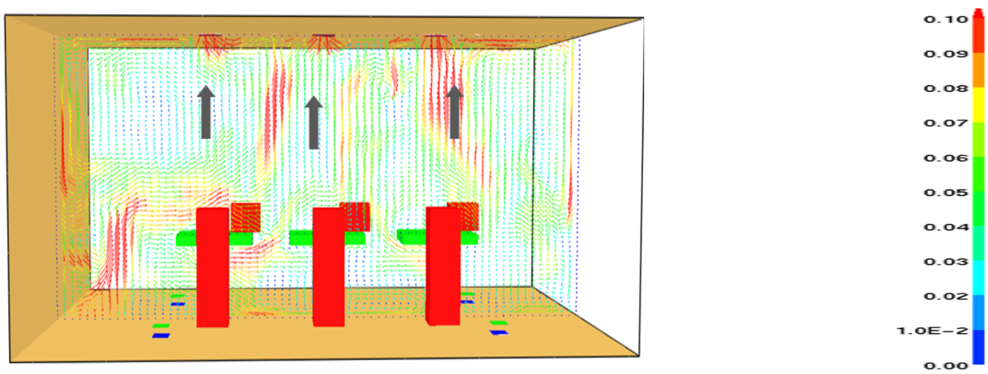


Figure 5: Air velocity distribution for case UFAD-2 [m/s]. The distinguishing airflow patterns are highlighted with grey arrows.

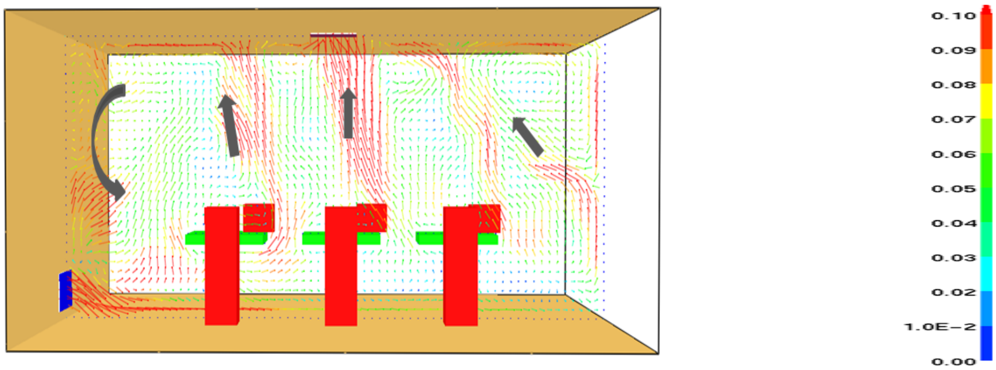


Figure 6: Air velocity distribution for case DV-1 [m/s]. The distinguishing airflow patterns are highlighted with grey arrows.

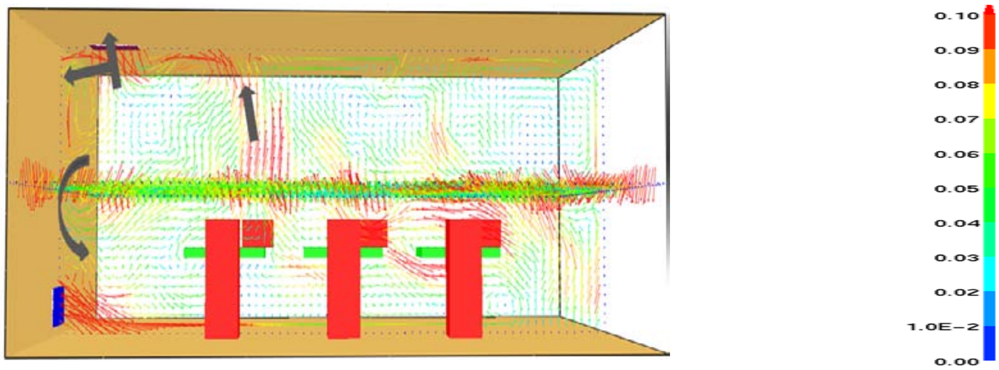


Figure 7: Air velocity distribution for case DV-3 [m/s]. The distinguishing airflow patterns are highlighted with grey arrows.

## DISCUSSION

The presented contaminant removal efficiency analysis shows that displacement ventilation is not always the best alternative to traditional mixing systems. The combination of floor mounted diffusers and wall exhaust can result in an asymmetrical distribution of $CO_2$ in the analyzed office, penalizing the persons closest to the exhaust. The discharge direction does not affect the breathing zone (1.1 m height) because the velocities involved are low. As a matter of fact, case 3 (UFAD-1) and case 5 (UFAD-3), with tangential or inclined flow, were comparable in terms of contaminant removal effectiveness and discomfort index.

When floor mounted diffusers are combined to ceiling exhaust, contaminant removal effectiveness increased significantly, particularly in the case the exhaust is located directly above the persons (case 4). However, the improvement is less evident if floor diffusers are distant from the desk: by comparing case 4 (UFAD-2) and 6 (UFAD-4) (Table 6), it is evident that if diffusers are moved 40 cm towards the walls (so that the distance from the desks is about 0.8 m instead that 0.4 m) the discomfort index ID% increased from 17.1% to 22.5%.

In order to better understand the phenomenon, it is important to analyze the velocity distribution in the room: due to the thermal plume, contaminants are entrained upwards, reaching the cold ceiling surface. At this point, only in the case the exhaust is placed on the ceiling, $CO_2$ is directly removed; on the contrary (i.e. in the case the exhaust is located on the walls), it takes longer for being exhausted. If air is supplied at floor level, at low velocities and at a significant distance from the desks, the effect of the of thermal plume is reduced. Also in the case displacement ventilation from wall diffusers it is evident that contaminants

are removed more efficiently from the center of the ceiling because of the smaller distance from the sources, as shown in Figure 6; on the contrary Figure 7 shows that a potential risk exists when exhaust is lateral because of the resulting air velocity directions. As a matter of fact, Table 4 shows that case 7 (DV-1) results in lower $CO_2$ concentration than case 8 (DV-2) and 9 (DV-3). When the room air flow patterns are markedly influenced by the direction of the supply discharge, such as in the case of displacement ventilation from wall diffusers, the wall mounting of the exhaust (case 10) can be effective in determining a uniform $CO_2$ concentration in the occupied zone. The performed study is consistent with Kobayashi and Chen [18] findings about the influence of the exhaust position on air quality in the case of floor supply displacement ventilation in small offices: they demonstrated that contaminants can be removed faster when exhausts are placed above the contaminant sources rather than in lateral position on the ceiling. However, results from numerical simulations should be completed by experimental tests investigating the effect of supply air terminals and exhaust positions on the resulting air quality.
As regards the mixing ventilation cases, in the case the inlet air velocity is low, because of its temperature (20°C) air falls at the beginning of the occupied zone; then it generally starts a horizontal movement under the tables towards the opposite wall, it gets warmer due to the presence of humans and pcs and it eventually rises upwards removing $CO_2$ from the occupied zone. Nevertheless, if the exhaust vent is on the wall opposite to the supply location, it is possible that a fraction of air is exhausted before it reaches the occupied zone; this can explain why the discomfort index ID [%] of case 2 is higher than that calculated for case 1 (Table 6).
The occupants position in the room was a relevant parameter: in this study it was assumed that occupants were seated at their desks, but if this is not the case, it can be thought that air from the floor could reach earlier the source. However the aim of this work was to compare different systems with the same layout of the room, and therefore only relative differences between contaminant concentrations for each case have been determined.

## CONCLUSION

A numerical investigation about the effects of the supply and exhaust locations on the $CO_2$ distribution in a typical office with cooled ceiling was carried out by means of computational fluid dynamics (CFD) methods. Two mixing ventilation configurations were compared with different displacement ventilation solutions with regards to the resulting $CO_2$ concentration measured in 23 positions which were recognized of being relevant for occupants' comfort. The percentage of dissatisfied due to the $CO_2$ concentration was calculated for all the sampling locations and a discomfort index for the whole office was introduced and determined. Finally, the contaminant removal effectiveness was calculated.
Results showed that mixing ventilation results in a higher contaminant removal effectiveness if exhaust and supply share the same wall. Displacement ventilation performance was very sensitive to the relative location of inlets and outlets. In the case of air supplied from the floor and exhausted from a sidewall, the corresponding contaminant removal effectiveness was lower than those resulting from the mixing ventilation scenarios and, in particular, the positions next to the exhaust were penalized. Nevertheless, if wall mounted displacement diffusers are adopted, the exhaust from a wall can be a good solution.
Finally it was found that the location of the exhaust on the ceiling, results in higher air quality levels regardless of the position of the inlet diffusers.

## ACKNOWLEDGEMENTS

This work was a part of a research program on radiant ceiling panels of Rhoss S.p.A., Italy.

## REFERENCES


[1] Wargocki, P., Wyon, D. P., Baik, Y. K Fanger, P O. 2000. *Productivity is affected by air quality in offices.* Proceedings of Healthy Buildings 2000, Vol.1, 635-640.

[2] Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., Fanger, P. O. 2000. *The Effects of Outdoor Air Supply Rate in a Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity*. Indoor Air 2000 (10), 222-226.

[3] CEN report CR 1752-1998. Ventilation for buildings- design criteria for the indoor environment. CEN/TC 156/WG 6.

[4] De Gids, W.F., Wouters, P. 2010. *$CO_2$ as indicator for the indoor air quality - general principles.* AIVC.VIP N°33 July2010.

[5] Persily, A.K., 1997. *Evaluating building IAQ and ventilation with indoor carbon dioxide*. ASHRAE Transaction 1997 Vol. 103 Pt 2.

[6] EN 15251-2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

[7] Mundt E., Mathisen, H.M, Nielsen, P.V., Moser, A. RHEVA Guidebook n°2. 2004.Ventilation effectiveness.

[8] Zhai, Z. J., Zhang, Z., Zhang, W., Chen, Q.J. 2007. *Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environment by CFD: Part 1-summary of prevalent turbulence models*. HVAC &R Resarrch (6), Vol 14.

[9] Lin, Z., Chow, T.T., Tzang. C.F., Fong. K.F., Chan. L.S.2005. *CFD study on effect of the air supply location on the performance of the displacement ventilation system*. Building and Environment 40 (2005), 1051-1067.

[10] Novoselac, A., Sbrebric, J. 2002. A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems. Energy and Buildings 34 (2002), 497-509.

[11] McGrattan, K., Hostikka, S, Floyd, J., McDermott, R. 2010. *Fire Dynamics Simulator (Version 5) Technical Reference Guide. Volume 3: Validation*. National Institute of Standards and Technology, NIST Special Publication 1018-5.

[12] Musser, A., McGrattan, K.B., Palmer, J. 2001. *Evaluation of a fast, simplified computational fluid dynamics model for solving room airflow problems*. National Institute of Standards and Technology (NIST), NISTIR 6760

[13] Lin, C.H., Wu, T.T, Horstman, R.H., Lebbin, P.A., Hosni, M.H., Jones, B.W, and Beck, B.T. 2006. *Comparison of large eddy simulation predictions with particle image velocimetry data for the airflow in a generic cabin model*. HVAC&Research, 12, 953 – 951.

[14] Cho, Y.H., Liu, M. 2010. *Correlation between minimum airflow and discharge air temperature*. Building and Environment, 45, 1601 – 1611.

[15] Farnham, C., Nakao, M., Nishioka, M., Nabeshima, M., Mizuno, T. 2011. *Study of mist-cooling for semi-enclosed spaces in Osaka, Japan*. Procedia Environmental Sciences, 4, 228 – 238.

[16] ISO 7726:1998. Ergonomics of the thermal environment - Instruments for measuring physical quantities, 1998.

[17] ASTM D6245-98 -2002. Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air.

[18] Kobayashi, N. and Chen, Q. 2003. *Floor-supply displacement ventilation in a small office.* Indoor and Built Environment, 12(4), 281-292.