Quantifying Airflow Mixing of Diverse Air Distribution Systems Using Taguchi Method and CFD Simulations

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Abstract

A novel modified decay method (MDM) has been developed to accurately estimate air change rates within non-uniformly mixed airspaces, relying on a proposed uniformity index (U_i). However, the MDM's applicability has yet to be extended, and to further advance its applicability, the U_i values should be quantified for various air distribution systems. Therefore, instead of modeling 700 CFD runs, only 27 simulated scenarios were conducted using the Taguchi method, covering the effect of six ventilation design parameters at three levels on airflow mixing. These factors are airflow direction, layout and shape of air terminals, air change rate, inlet temperature, and source location. Findings showed that the source location strongly affects airflow mixing by 83%, followed by the air change rate (inlet velocity) by 7%, and the third is the inlet temperature by 5%. Tabulated values of U_i were generated for various air-distribution systems to extend the applicability of the MDM.

Introduction

Air distribution systems significantly impact thermal satisfaction, indoor air quality (IAQ), and energy-efficient indoor environments (Awbi 1998). There are several drawbacks resulting from poor airflow distribution, such as discomfort, draft, respiratory-related diseases, and high levels of energy consumption (Cheng and Lin 2015). Accordingly, there is a growing interest, especially during this post-COVID-19 era, to improve air distribution systems and thereby offer better airflow mixing levels indoors (Arjmandi, Amini et al. 2022). Therefore, accurate evaluation of airflow mixing is paramount for the selection and design of an optimal air distribution system.

A review study (Cao, Awbi et al. 2014) discussed the ventilation effectiveness and airflow distribution systems for various spaces to identify the most suitable room air distributions. It was revealed that different ventilation methods have been employed in buildings for different tasks. The same study divided, as commonly known, ventilation systems into two modes, namely mixed ventilation (MV) and displacement ventilation (DV), according to concentration distribution. MV is a conventional air distribution mode to control the indoor environment. However, the DV was primarily employed to reduce energy consumption and enhance the indoor air quality in the breathing zone.

Another study (Chau, Zhou et al. 2018) compared both ventilation modes in terms of the air change rate, temperature profile, transmission of particulate matter (PM), and CO_2 concentrations. It was found that the vertical profile of temperature differed; however, the volume-average temperature difference was one degree Celsius. The temperature profile of MV was relatively homogeneous, while in DV it was linearly varied with the height, i.e., lower temperature at the floor and maximum temperature at the ceiling level. Due to the stratification effect, the CO_2 concentration of MV was higher than that of DV by fourfold. However, the PM concentrations were similar for both ventilation modes.

The same review study (Cao, Awbi et al. 2014) investigated the effect of different arrangements of inlets and outlets on airflow distributions. It was revealed that the uniformity of temperature and contaminant fields is influenced by a properly designed system. In this regard, it should be mentioned that increasing air change rates to enhance ventilation performance is associated with the position of inlets and outlets (Krajčík, Simone et al. 2012).

On the other hand, several studies compared MV and DV to quantify the dispersion of tracer gas concentrations using field measurements and numerical modeling. He et al. (He 2005) traced SF_6 to measure its dispersion from the floor surface and found that the dispersion was non-uniform using MV, while DV stratification resulted in a higher concentration at the upper level and a lesser concentration at the lower level. The dispersion of particles is introduced by several studies comparing the performance of both MV and DV. Two studies (Qian 2006, Olmedo, Nielsen et al. 2012) confirmed the well-mixed dispersion of pollutants in MV, while that dispersion was locked inside the breathing zone due to thermal stratification in DV.

During the COVID-19 pandemic, whether DV or MV works better has been debated. The results are controversial; some studies showed that MV mitigates the risk of exposure to the virus (Qian 2006, Pei, Taylor et al.

2021). However, some authors have come to a conflicting conclusion (Bhagat, Wykes et al. 2020). These contradictory results were justified by a review study (Rayegan, Shu et al. 2023), to successfully lower the infection risk by maintaining an adequate air change rate, displacement ventilation must be properly designed; otherwise, it will not function as intended.

In summary, as shown in the literature, the two ventilation modes (MV) and (DV) have several geometry configurations and airflow characteristics. Each ventilation mode has its benefits and drawbacks, which should be considered. The results of previous studies are controversial as a function of the architectural configuration of the space. These results cannot be generalized, and it is not possible to draw a general rule that applies to other cases. Consequently, both ventilation modes with various airflow distributions should be considered in quantifying the airflow mixing using tracer gas techniques (ASTM 2017).

Computational Fluid Dynamics (CFD) simulations have been widely used to accurately predict airflow mixing for various ventilation studies. However, the large number of simulation parameters makes it a challenge to examine all cases. Therefore, coupling CFD with statistical methods could overcome this limitation. This approach showed successful results in solving problems in the ventilation field (Metzger 2011, Deng, Cooper et al. 2017, Haghshenaskashani, Sajadi et al. 2018) and other different domains (Sahu and Sahu 2017, Khanjanpour and Javadi 2021). Instead of examining all possible combinations of the full-factorial parameters to quantify the airflow mixing for various air distribution configurations, a statistical method such as the orthogonal array technique using the robust design of Taguchi (Taguchi 1986) has been commonly applied to design the simulation matrix involving a limited number of CFD runs that covers the entire parametric space. Using this approach draws solid conclusions without reducing the simulation outcomes' credibility and power.

For many decades, the term ventilation effectiveness (VE) has been a quantitative index that usually measures airflow mixing in ventilated spaces. VE is significantly influenced by both space geometry and the arrangement of inlets and outlets (Chung, Hsu et al. 2001), and more details are described in ANSI/ASHRAE 129 (ASHRAE 129 2002). A recently published work (Reda, Ali et al. 2023) discussed the limitations of VE in terms of zone distribution effectiveness as a mixing factor, showing its limitations for the accurate prediction of airflow mixing. The authors showed that existing data on such metrics are inaccurate in addition to they are subjective, roughly estimated, and inconsistent across different standards (e.g., AIHA and ASHRAE). Further, they developed a new airflow mixing index to cope with these limitations, i.e., a uniformity index (U_i) that is defined as the minimum to average tracer concentration at the breathing level. They showed that the U_i has a higher accuracy, which might reach 18%, to quantify tracer-air mixing if compared with the zone distribution effectiveness (E_z). The U_i value could be calculated using CFD simulations or field tracer measurements. However, the U_i values are still not generalized for various air distribution systems. Besides, the well-known decay method tends to underestimate air change rates in ventilated spaces due to the well-mixed assumption. Therefore, a modified decay method (MDM) was developed to be used in non-uniformed airflow mixed spaces, which requires identifying the U_i value first (Reda, Ali et al. 2023).

Therefore, to fill these knowledge gaps, many CFD tracer simulations were conducted to quantify the airflow mixing level using the uniformity index (U_i) for various air distribution systems, including both ventilation modes (mixed and displacement). Various ventilation settings and scenarios were considered to analyze multiple factors simultaneously at different levels. The full factorial of this CFD-parametric study exceeds 700 CFD runs, which is decreased using the partial orthogonal array technique, or the so-called Taguchi method. Quantifying the U_i values for a diverse array of ventilation scenarios and spatial configurations extends the applicability of the MDM.

Method

Taguchi method

The Taguchi method (Taguchi 1986) offers a unique design of orthogonal arrays to model fewer simulations for analyzing the desired airflow mixing (response) according to pre-defined factors. This orthogonal array was selected according to the total degree of freedom (DOF). For each factor, the DOF is one less than the number of factor levels. This number should be smaller than the overall DOF of the selected orthogonal array. In this study, Taguchi orthogonal array L27 (3^9) was used, consisting of six factors with three levels, as shown in Table 1.

Table 1: Studied factors and levels on airflow mixing in a single zone.

Level	Flow direction	Layout	Terminals shape	Air change rate [h^{-1}]	Inlet temperature [°C]	Source locations
1	C2C[1]	SISO[4]	Square	6	14	4
2	W2W[2]	DIDO[5]	Round	9	22	8
3	F2F[3]	TITO[6]	Linear	12	30	41

[1]ceiling-to-ceiling airflow.
[2]wall-to-wall airflow.
[3]floor-to-floor airflow.
[4]single inlet single outlet.
[5]double inlets double outlets.
[6]triple inlets triple outlets.

Ventilation modes, either mixed or displacement, are considered through three levels as a flow direction enters and leaves the zone from the ceiling (C2C) or from the floor (F2F), both representing mixed ventilation, while when it enters and leaves from opposite walls (W2W), it represents displacement mode. Besides, the placement and number of inlets and outlets are also considered for three levels, i.e., single, double, or triple air terminals. Further, three common shapes of air terminals are modeled in the form of squared, round, and linear diffusers. Also, considering the recommended air change rates of 6-12 h^{-1} are usually applied in classrooms. Moreover, the recommended cooling and heating inlet temperatures as well as an average value are also considered. Lastly, the source location is modeled using 4-spherical mid-points, 8-spherical sided-points, and realistic 41-mouth openings for occupants, all of which have the same surface area (0.0004 m^2).

Taguchi calculations begin with quantifying the signal-to-noise (S/N) ratios for each factor, which means the ability of airflow mixing to resist variations caused by investigated factors, followed by identifying the delta values from the S/N minimum and maximum ratios, and lastly, ranking the order of each factor. The S/N ratio is identified as the larger is the better, i.e., the higher value of the uniformity index (U_i) represents a higher level of airflow mixing as expressed in Equation (1). Ultimately, the optimal combination of factors and levels was tested to achieve the best combinations of investigated factors for a better airflow mixing level. After calculating the S/N ratios, the contribution ratio of each factor to airflow mixing is identified using the analysis of variance (ANOVA) test.

$$S/N = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i{}^2}\right) \quad (1)$$

where Y_i represents the predicted uniformity index value for the ith study case and n is the number of simulations.

CFD model

Computational domain: A 3D geometry of a classroom with nine different arrangements was established for this CFD-parametric study. The classroom has a floor area of 78 m^2 and a height of 3.4 m to accommodate 40 students and one instructor. A simplified human model was considered at seated and standing positions to mimic occupants. Anthropometric dimensions were considered for human body modeling according to available data on BS EN ISO 7250:1998 and PD ISO/TR 7250-2:2010 in addition to consulting relevant handbooks (Ashby 1986, Majumder 2014). The interior furniture was only modeled as wooden desks. Other interior surfaces (walls, windows, ceilings, floor… etc) are defined in the boundary conditions section.

Meshing: At an early stage, a mesh sensitivity study was carried out to decrease the error associated with mesh resolution and to minimize the solution time. Based on that, the classroom domain was discretized into 5 million unstructured tetrahedral elements. The mesh was then refined by adding an inflation of ten layers with a high-smooth transition of growth rate equal to 1.2 around occupants, desks, sources, and air terminals. These improvements result in a refined mesh with an average skewness of less than 0.3 and an average orthogonal quality greater than 0.7. Figure 1 shows one sample of the nine modeled geometries for the classroom used in this study, as well as the meshing views.

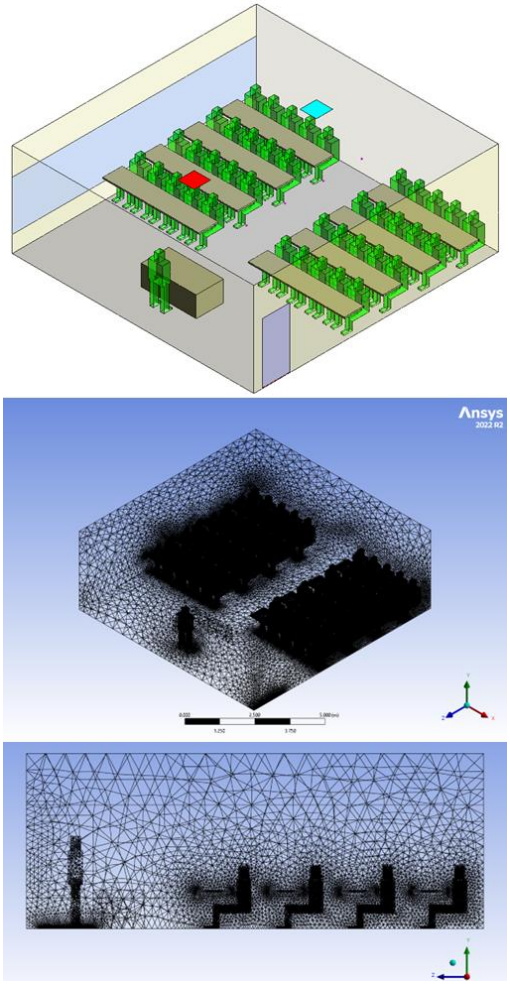

Figure 1: Sample of modeled geometry for the classroom used in this study (upper) in addition to 3D and sectional meshing views (middle and lower).

Boundary conditions: Realistic and accurate boundary conditions (BCs) were considered using previous settings and collected data conducted in the same classroom (Reda, Ali et al. 2023). The thermal characteristics of interior surfaces, inlets, outlets, and occupants are listed in Table 2.

Solver settings: ANSYS fluent V22R2 was used to compute steady-state analysis of airflow field, heat transfer, and CO_2 spatial distribution in the classroom. A multi-species air mixture is governed by continuity, momentum, energy, and species transport equations. The mathematical formulas of the latter equations are explained in detail in this study (Ning, Mengjie et al. 2016). The SST turbulence model (Menter 1994) was employed in this study to predict the air velocity and temperature fields due to combining the advantages of k-ε and k- ω (Stamou and Katsiris 2006).

Model validation: As a second stage of the preliminary simulations, the developed CFD model was validated using the CO_2 data collected in our previous study (Reda, Ali et al. 2023). For this purpose, the root mean square error of CO_2 concentration logs (RMSEL) as described in equation 2 was used. The predicted CO_2 concentrations at most locations were close to the measured data, except for four locations around the source due to the proximity effect, especially those positioned between the source and the outlet. Generally, the CFD model shows a good agreement against field-collected data with a RMSEL value of less than 12%.

$$\text{RMSEL}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\log C_i-\log \widehat{C}_i\right)^2} \quad (2)$$

where Ci and $\widehat{C}_i$ are the measured and predicted CO_2 concentrations respectively.

Table 2: Boundary conditions of the CFD model employed in this study.

Type	Named selection	Settings
Inlet	Supply diffusers	Velocity-inlet V_{in} = 0.41 – 2.47 m/s T_{in} = 14, 22, 30 °C X_{CO2} = 0.0004
Outlet	Return grilles	Pressure outlet 0 Pa (gauge)
	Door undercut	
Wall	Ceiling	No slip Adiabatic
	Desk	
	Door	
	Floor	
	Walls	
	Window	
	Occupants	Heat flux of 60 W/m^2
Source	4-points	Mass flow inlet 0.0001 kg/s 33 °C X_{CO2} = 1
	8-points	
	41-points	Ditto, but X_{CO2} = 0.04

Index of airflow mixing

As explained in the literature, existing airflow mixing indexes such as zone distribution effectiveness (Ashrae 2019) are limited to accurate prediction. Therefore, in this study, the uniformity index (U_i) was used as expressed in Equation (3) to quantify the airflow mixing level for each of the 27 simulated cases. Simply, the U_i is defined as the minimum to average CO_2 concentrations at the breathing level.

$$U_i=\frac{C_{min}}{C_{avg}} \quad (3)$$

where U_i is uniformity index; C_{min} and C_{avg} are minimum and average tracer concentrations at the breathing level.

Results and discussion

The conducted CFD simulations are discussed in this section, which is divided into three sections. First, the CO_2 spatial transport at the breathing level is analyzed, followed by ranking the six investigated factors affecting the airflow mixing. Eventually, to investigate the main goal of this work, i.e., generating tabulated values of the uniformity index (U_i) for various air distribution systems.

CO_2 distribution at the breathing level

Among the 27 simulated cases, three samples are selected for discussing how CO_2 transports at the breathing level, representing different airflow directions. Figure 2a represents a mixed ventilation mode that shows the air entering and leaving the classroom through a single square ceiling diffuser. In this case, the CO_2 was injected from four middle points located in the middle between the two groups of students. The propagation of CO_2 is observed except for the one source located beneath the supply inlet; the airflow jet forces the CO_2 flow to move downward, not horizontally like other sources. The mean CO_2 concentration at the breathing level is 1360 ppm, while at the outlet it is 795 ppm.

Figure 2b shows one of the displacement ventilation scenarios simulated using two linear inlets and outlets. The CO_2 was injected at eight-sided locations. The predicted CO_2 concentrations are quite higher at the breathing level compared to the previous case, showing a mean value of 3014 ppm. However, it remains slightly unchanged at the outlet with 802 ppm. Another major difference between these two cases is the minimum reported CO_2 value. Figure 2b shows a lower minimum concentration of 491 ppm if compared to the value reported in Figure 2a (621 ppm). This can be justified since the inlet location is closer to the breathing level in case 2, especially since the rear side of the classroom is exposed to minimum CO_2 concentrations.

In another simulated case using a mixed ventilation mode; contrary to earlier, the air was supplied and left the classroom from the floor (Figure 2c) using triple-rounded diffusers. In this case, the CO_2 injection was realistically modeled as being exhaled from all occupants' mouth openings. This results in a CO_2 concentration at the breathing level and outlets of 904 and 626 ppm, respectively. However, the minimum CO_2 concentration is 613, which is close to the first case.

For all 27 simulated scenarios, it is observed that the CO_2 spatial distribution varies according to the source locations. Comparing four-middle points with eight-sided locations shows the mean CO_2 concentrations are doubled (1316 ppm becomes 2572 ppm). These two cases used pure CO_2 injection settings (mole fraction of unit); however, realistic exhaled CO_2 was emitted at 0.04 less than the latter value. For this reason, when testing 41-point source locations, the mean CO_2 dramatically decreased to 885 ppm. In addition, the isentropic dissemination of CO_2 using a spherical shape is quite different from the surface shape (mouth). These two limitations should be considered while considering comparing CO_2 levels for different source locations.

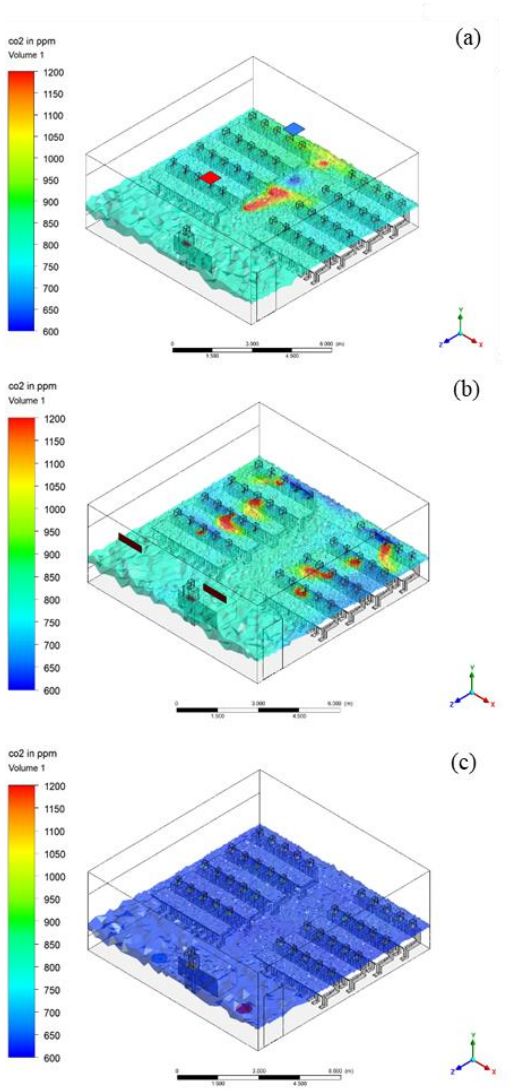

Figure 2: ISO-volume CO_2 contours at breathing levels in the studied classroom (1 m from the floor) for various air distribution scenarios (a) mixed ventilation using a ceiling inlet with a square shape; (b) displacement ventilation using wall inlets with a linear shape; and (c) mixed ventilation using floor inlets with a round-shape.

Factors affecting airflow mixing

In Figure 3, six factors (referring to Table 1) are tested simultaneously to measure their influence on airflow mixing. Taguchi's analysis using larger the better criteria coupled with analysis of variance (ANOVA) to calculate the contribution rate of each parameter based on the calculated signal-to-noise ratios (S/N) shows that the source location is the most contributing factor by 83%. The air change rate (inlet velocity) is the second-ranked factor at 7%, and the third is the inlet temperature at 5%. Minor contributions are attributed to the airflow direction and arrangement of air terminals, which are equally ranked at 2%, as well as terminal shapes at 1%.

ANOVA analysis shows that the source location has the highest F- statistic (55.1) and a very low p-value (0.000), which suggests a strong effect, i.e., the source location significantly impacts the S/N ratio. The air change rate also shows a significant effect with a F-static of 4.3 and a p-value of 0.03. Inlet temperature has a borderline effect with a p-value of 0.06. Other factors have a p-value greater than 0.05, indicating no statistically significant effect on the means of the S/N ratio. In Figure 3, the x-axis of the plot shows the three levels of each factor. The y-axis shows the mean of the S/N ratio for each level of the factor. It appears that the 41-point source location at level three has the biggest impact on airflow mixing compared to the other two levels. The air change rate also shows some effect, with a S/N being slightly higher at 12 h^{-1}. Other factors have a minor effect, with unclear trends in the S/N ratios.

Based on these findings, higher levels of airflow mixing could be achieved using a mixed ventilation mode designed at higher air change rates. Linear air terminals are recommended for better airflow mixing, while other factors could not be generalized in this study. A study (Yuce, Aganovic et al. 2023) found that inlet velocity (air change rate) is the most influential factor on tracer (CO_2) transmission among the investigated ventilation parameters. In addition, other factors like inlet temperature, placement of air terminals, and room height showed different impacts on CO_2 concentrations. However, they ignore studying the source location effect on tracer-air distribution. Further, the authors recommend directed airflow toward the source to minimize tracer transport, which is similar to our observation here (Figure 2a). Also, they found that zone geometry is the least influential in tracer transport, aligned with selecting a generic geometry in this study that complies with standard recommendations.

U_i values for various air distribution scenarios

A wide range of uniformity index (U_i) values are generated as shown in Table 3, representing various scenarios of ventilation modes with different airflow

directions clustered according to the placement of air terminals. The minimum and maximum U_i values are identified according to the applied range of air change rates (6-12 h^{-1}). Comparing airflow mixing under different air change rates for various airflow directions is presented in Figure 4. It could be concluded that the average value of U_i equals 0.73 among the 27 tested CFD cases. The minimum reported value of U_i is found while using displacement ventilation (0.37), while the maximum is attained by mixed ventilation (0.94). The ceiling-inlet mixed ventilation mode shows an average U_i value (0.67) higher than the floor-inlet mode (0.59) at the minimum air change rate (6 h^{-1}); in contrast, the average U_i value is found to be higher when using floor-inlet mixed mode (0.93) at a higher air change rate (12 h^{-1}).

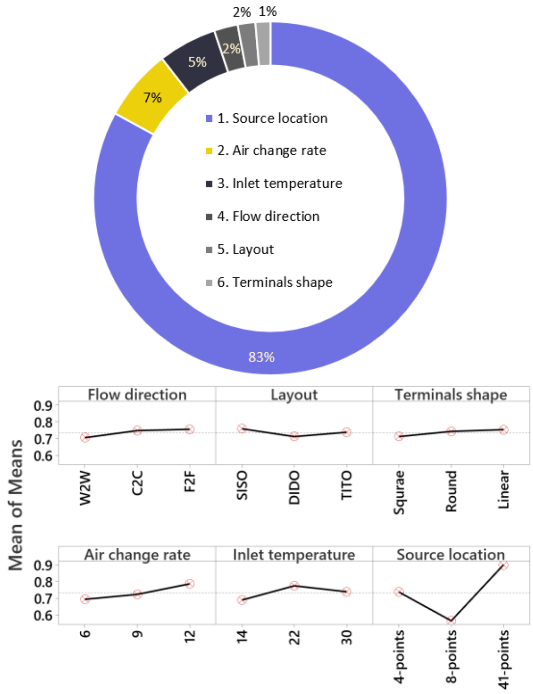

Figure 3: Factors affecting airflow mixing in this study, including the ranking and contribution of each factor (upper) in addition to the mean of the signal-to-noise ratio(lower). W2W: wall-to-wall airflow; C2C: ceiling-to-ceiling airflow; F2F: floor-to-floor airflow; SISO: single inlet single outlet; DIDO: double inlets double outlets; TITO: triple inlets triple outlets.

As shown in Figure 4, using linear regression analysis, the air change rate strongly affects the airflow mixing (R^2 = 1), while the air terminal trends show unclear relationships. It is intuitive that when the supply air flow rate increases, the dilution of tracer concentration is higher, causing a high level of airflow mixing. For ceiling-inlet mixed ventilation, a larger number of inlets achieves higher airflow mixing levels, which is commonly understood. A previous study (Khan, Feigley et al. 2006) showed that ceiling inlets provided the space with uniform airflow mixing (tracer concentrations), while the type of air terminals had a negligible effect on the breathing zone and space average concentrations. In contrast, we found that for displacement ventilation, the U_i value is inversely proportional to installing more inlets. This might be caused by the proximity effect; being near inlets forms a turbulence effect that prohibits higher levels of airflow mixing. For floor-inlet mixed ventilation, the correlation is poor (R^2 = 0.52) to draw a generalized conclusion; however, the airflow mixing remains unchanged at different air terminals. This requires further investigations for this kind of ventilation modes.

Table 3: Calculated values of uniformity index (U_i) for different ventilation scenarios.

Ventilation mode	Air terminals	Uniformity index (U_i)
Mixed ventilation with ceiling inlets	SISO[1]	0.59 – 0.86
	DIDO[2]	0.64 – 0.85
	TITO[3]	0.77 – 0.90
Displacement ventilation	SISO	0.54 – 0.94
	DIDO	0.41 – 0.88
	TITO	0.37 – 0.91
Mixed ventilation with floor inlets	SISO	0.60 – 0.94
	DIDO	0.65 – 0.93
	TITO	0.51 – 0.91

[1]single inlet single outlet.
[2]double inlets double outlets.
[3]triple inlets triple outlets.

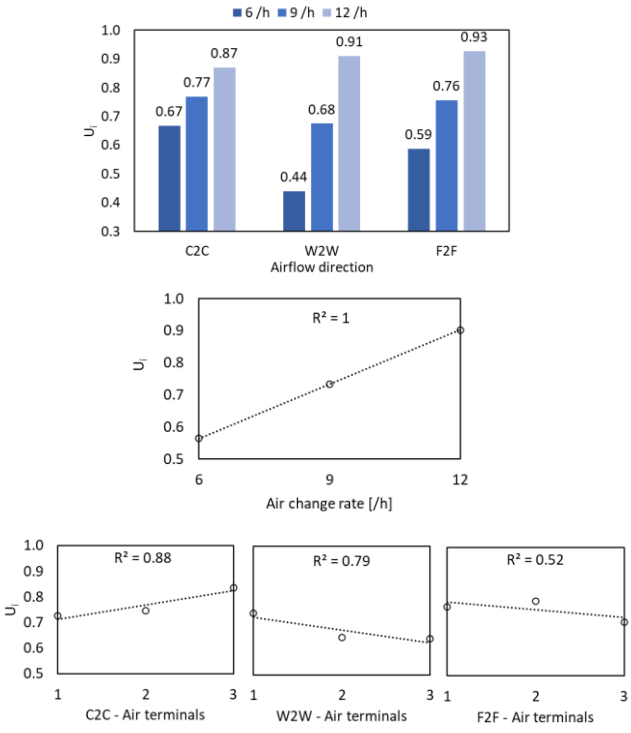

Figure 4: Effect of air change rate (upper and middle) and ventilation modes (lower) on airflow mixing. C2C: ceiling-to-ceiling airflow; W2W: wall-to-wall airflow, F2F: floor-to-floor airflow.

Conclusions

A total of 27 CFD simulations were carried out in a single zone to study the effect of six ventilation factors (airflow direction, layout and shape of air terminals, air change rate, inlet temperature, and source location) on airflow mixing at three levels. For this purpose, many air distribution systems were assessed for mixed and displacement ventilation modes. The CFD model was validated with previous field-collected tracer data in a similar classroom. A statistical method (Taguchi) was coupled with the CFD simulations to first decrease the number of CFD runs using the orthogonal array approach and later analyze the signal-to-noise (S/N) ratio for each factor. Using the calculated S/N ratios, the analysis of variance (ANOVA) test was employed to rank the contribution of each investigated factor. A uniformity index (U_i) was used to quantify the airflow mixing at the breathing level for each simulated scenario. The study yields the following findings:

- The source location strongly affects airflow mixing by 83%, followed by the air change rate (inlet velocity) by 7%, and the third is the inlet temperature by 5%. Minor contributions to airflow mixing are attributed to the airflow direction and arrangement of air terminals, which are equally ranked at 2%, as well as terminal shapes at 1%.
- Among all simulated cases, an average value of U_i equals 0.73 was found. Displacement ventilation showed the least U_i value (0.37), while the maximum is reported by mixed ventilation (0.94). Mixed ventilation mode with ceiling inlets at a minimum air change rate of 6 h^{-1} revealed an average U_i value of 0.67, which is higher than the 0.59 value in the floor-inlet mode. However, if we crank up the air change rate to 12 h^{-1} and switch to the floor-inlet mixed mode, the average Ui value jumps to 0.93.
- Tabulated values of the U_i (Table 3) developed for various air-distribution systems of mixing and displacement ventilation modes could extend the applicability of the novel modified decay method (MDM), which accurately estimates air change rates within non-uniformly mixed airspaces relying on the U_i.
- Increasing the number of inlets and outlets improves the airflow mixing for mixed ventilation mode with ceiling inlets. In contrast, it deteriorates the mixing level in the case of displacement ventilation mode.

This study employed a generalized zone geometry according to recommended international standards since it has a minor effect on airflow mixing using tracer gas transport (Yuce, Aganovic et al. 2023). As a first phase, only six ventilation factors were studied from the perspective of airflow mixing at three levels. In a subsequent second phase, the three major contributing factors to airflow mixing (source location, air change rate, and inlet temperature) could be detailed using a wider range of probabilities/levels. As concluded before in the literature, we confirm the mixed ventilation mode has higher airflow mixing if compared to the displacement ventilation mode. Still, the placement and number of air terminals show unclear effects on airflow mixing while using floor-inlet mixed ventilation mode. This finding should be further investigated in future studies.

On the other hand, coupling statistical methods (e.g., Taguchi and INOVA) with CFD simulations is a powerful tool to narrow down experiments/modeling scenarios without losing the entire characteristics and power of full factorial analysis, in addition to showing solid results. With fewer studies progressing, the ventilation field lacks more trials using this approach.

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