A Comparison of Indoor Pollution using Different Ventilation Methods: A Case Study

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Abstract. One of the essential aspects of healthy buildings is the air quality that people breathe indoors, as it directly impacts their comfort, health, and well-being. Achieving an acceptable indoor air quality (IAQ) has become an essential design objective for newly constructed and renovated buildings as well as for the operational system in existing buildings. The COVID-19 pandemic, which began in 2019, highlighted the need for better IAQ. The quality of indoor air space is not only affected by ambient or external pollution but also by indoor sources and inadequate ventilation. For instance, the build-up of pollutants may differ for the same space due to the ventilation method. This paper uses a case study of an open-plan office in Loughborough, UK, simulated under two ventilation schemes, mechanical ventilation (MV) and natural ventilation (NV), for the same weather file to diagnose and examine the difference in the IAQ. The results of the simulations were compared with monitored data using an IAQ sensor located in the centre of the open-plan office. The air parameters measured were indoor temperature (Ta), relative humidity (RH), carbon dioxide (CO_2), formaldehyde (CH_2O) and particulate matter ($PM_{2.5}$). It was found that the average CO_2 levels were better by 10% under MV than in NV because higher ventilation rates were achieved during occupied hours. The average $PM_{2.5}$ was twofold better under NV than MV, as well as CH_2O was also better under NV than MV by 26% in the simulated scenarios. The open-plan office was ventilated at all times under NV; unlike in MV, the air handling unit was only operating during the occupied hours, which contributed to better IAQ. The simulation results for this study revealed that both mechanical and natural ventilation could achieve acceptable IAQ for this specific case study and location. The ventilation control strategy is the manipulator of jeopardising the IAQ in the space.

Keywords. IAQ, mechanical ventilation, natural ventilation, IAQ monitoring, open-plan work environments
DOI: https://doi.org/10.34641/clima.2022.315

1. Introduction

The quality of the air people breathe indoors directly impacts their health [1], well-being and productivity [2] and constitutes one of the most important aspects of healthy buildings. The usual way of diluting and controlling indoor air pollution is via ventilation. The purpose of ventilation is to supply fresh air as well as meeting the heating/cooling requirements and air quality of occupants within an indoor environment [3]. Ventilation could be introduced to the indoors either naturally or mechanically. The adjective "natural" differentiates the driving force causing the air movement compared to a "mechanical" means.

Indoor pollutants are derived from both outdoor and indoor sources. These sources impose different requirements on the ventilation control strategies needed to secure good health and comfort conditions. It is essential to know the outdoor pollution to limit its entry to the indoor space via the ventilation system and openings [4], while also knowing the spatial distribution during the day. Understanding the outdoor pollution and observing its trend may be used to control the ventilation system and limit the entry of pollutants at peak levels. On the other hand, indoor pollutants are present due to many sources found in the building, both chemical and biological. Sources such as building materials, cleaning products, furnishings and fabric, equipment and electrical appliances, and pollutants resulting from occupants' presence or activities, etc [5]. The actual pollutants and pollutant sources present in a building will largely be determined by the type of building and its usage. For example, residential buildings are likely to have greater diversity (and certainly a different range) of pollutants and pollutant sources than in a typical office.

One of MV's advantages over NV is that it can filter and trap particles and gaseous pollutants [6]. Consequently, better IAQ is better achieved through MV than NV [7]. The scope for filtering or treating the supply of exhaust air is very limited with NV. This is because the flow-inducing pressures involved are low, so any increase in resistance to flow, for example, imposed by filters, would substantially reduce the effectiveness of NV [8]. However, in the last few years, the air in many megacities has become so heavily polluted with gaseous substances and particles that it is no longer advisable to ventilate interior spaces with unfiltered outside air [9]. Therefore, NV is limited in heavily polluted environments, and MV is almost independent of weather conditions. However, both ventilation approaches have the potential to increase concentrations of outdoor pollutants into the indoor space [10,11].

One of the critical needs associated with controlling air pollution (generally indoors and outdoors) is continuous air pollution monitoring. With the increased attention to the importance of air quality, especially indoors, the continual development of low-cost sensor technology for monitoring purposes made it much more feasible to use in different indoor sectors [12-15]. The selection of the air quality sensor is based on reliability, accuracy, resolution, autonomy, and response time [12]. Continuously monitoring regularly occupied spaces using accredited monitors such as those referred by RESET Air [16] has become a necessity for any building to be rated as a healthy environment.

Offices are a typical building type that is operationally amenable to both ventilation types, MV and NV [11]. A design question would be encountered by the building services engineer, would NV work for a proposed building given activities therein, its form, shape, construction method and material used in the proposed location[5]? To assess the impact of these different modes of ventilation on IAQ, the current paper uses an open-plan office in Loughborough UK and simulate it under the two ventilation systems, MV and NV, using IAQ and a ventilation analysis computer program. The open-plan office is originally mechanically ventilated and includes an IAQ sensor located in the centre of the office and measures indoor temperature (Ta), relative humidity (RH), carbon dioxide (CO_2), formaldehyde (CH_2O) and particulate matter ($PM_{2.5}$). The results of the simulations were compared and analysed to determine if acceptable levels of IAQ can be achieved by NV. The results of the simulations of the MV were compared with the real-time measured data. The real-time measured data were analysed to allow more informed decision-making about the indoor pollution found in the office for each ventilation mode and propose an appropriate control strategy accordingly.

2. Methodology

2.1 Case Study

The open-plan office is located on the ground floor of a two-story building oriented southwest (with a degree angle of 208° relative to the north) in Loughborough, UK. The area and the volume of the office are 148.5m^2 and 445.5m^3, respectively. The external façade of the office includes six windows of the same shape, type, and dimension. The office can accommodate up to 19 occupants. The occupancy hours are from 08:00 to 18:00 Monday to Friday but also open at the weekends. The type of activity work is sedentary office work. The open-plan office is mechanically ventilated with the supply and extract diffusers at ceiling level (mixing ventilation), as shown in Fig.1. The open-plan office includes an EnLink IAQ sensor [17] located in the middle of the room at a height of 1.1 meters [18]. An overview of the accuracy of the measurements using the EnLink IAQ sensor is available in the appendices.

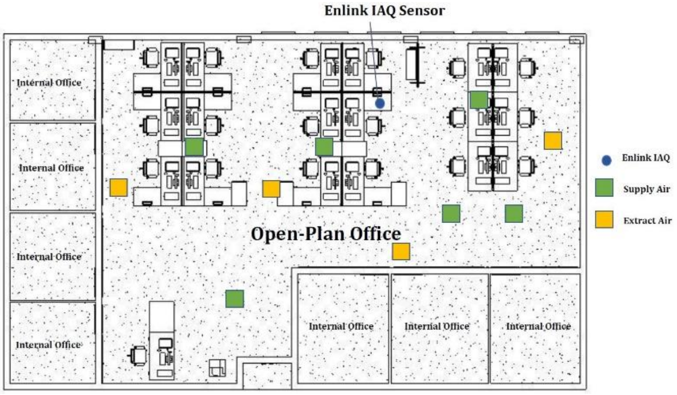

Fig. 1 - Examined open-plan office layout, including the occupant workplaces, IAQ sensor location, and supply and extract air diffusers at the ceiling level.

2.2 Simulation Setup

The simulations were carried out using CONTAM [19], a multizone building airflow and contaminant transport computer program often used for ventilation and IAQ analysis. It was developed at the National Institute of Standards and Technology (NIST) in the USA. It helps determine airflows, contaminant concentrations and personal exposure.

The simulation method for the airflows and contaminants was set to be transient to obtain time histories of airflow rates, pressure differentials and contaminant concentrations under changing ventilation systems. The simulation period and time were set from 25th of May 00:00 to 31st of May 23:59. The monitored period was the same as the simulated period.

The interior leakage was assumed to be uniformly distributed. It does not account for the leakage pathways associated with interstitial spaces that almost always exist within buildings. The effective leakage areas and wind pressure coefficient for the external wall (Cp=0.6) were taken from the library manager of CONTAM [19]. To verify that the defined building surface areas and the associated leakage rates are correct, a simulated building pressurisation test was performed and compared against CIBSE Guide TM23.

2.3 Comfort Criteria

The recommended comfort criteria for the open-plan office are summarised in Tab.1[5]. The outdoor air rate was based on the floor area of the space as the number of occupancies was unknown for the monitored period. The outdoor air requirement for the office with full occupancy was found to be 383.05 L/s. For every occupant in the simulation, a CO_2 generation rate was defined (0.0052L/s), and a prescribed removal rate of 10 L/s/person was added as recommended by guidelines. The prescribed outdoor air supply rates are based on the metabolic pollutants of occupants according to their activity or to the size of the space. For sedentary office work, the minimum ventilation rate is 10 L/s per person for an office. The outdoor air supply per m^2 was set to 1.3 L/s [8]. Thus, the rates at which the main air handler unit delivers outdoor air are proportional to the floor area in the MV scenario. No windows were opened in the MV scenario, and no filters were added.

For the NV scenario, the office was ventilated by using windows. The area of each opening required to give a ventilation rate for a specified height value was calculated using the CIBSE ventilation tool [20]. The approximate opening area required for each window in the office to supply the sufficient ventilation rate was found to be 0.28 m^2.

Tab. 1 – Air parameters and key pollutants in offices.

Air parameter	Impact	Comfort range	Evaluated
Ta	Working in hot conditions can cause heat stress, discomfort, and heat exhaustion. Also, it can lead to reduced performance, more mistakes and, depending on the extremities, several disorders. [3]	22-25°C [5]	Yes
RH	Low RH levels can give rise to respiratory discomfort and nuisance from electrostatic effects [8,22]. High RH levels incurs the risk of condensation and mould growth on surfaces that have temperatures that fall below the dewpoint temperature of the air [8,22].	40-60% [5]	Yes
Metabolic CO_2	Indoor CO_2 can significantly impact productivity and decision-making capabilities [23]. Indoor CO_2 levels <1000-1500 ppm contribute to symptoms such as headache, dizziness, tiredness, and difficulties concentrating [23-25]. Indoor CO_2 levels above < 2,500 ppm contribute to unsatisfactory performance by occupants and loss of concentration [23] , especially when exposed for 2.5 hours or more [24].	Acceptable 1000 ppm [24] Not to exceed 1500 ppm [25] Dangerous 5000 ppm [26]	Yes
CH_2O * Very volatile organic compound (VVOC)	When formaldehyde is present in the air at levels exceeding 0.3 -3.2 ppm for 35 minutes, individuals may experience throat irritation, an increase in the eye-blinking rate, eye irritation, nose irritation, and a desire to leave the room [27].	Acceptable 1000 ug/m^3 [27, 28] Not to exceed 2500 ug/m^3 ≈2 ppm [26]	Yes
$PM_{2.5}$	Particles in the $PM_{2.5}$ size range can travel deeply into the respiratory tract, down into the lungs' deepest (alveolar) portions, where gas exchange occurs between the air and the bloodstream [29]. The alveolar portion of the lungs has no efficient means of removing PM2.5 [30]. Exposure to fine particles can cause short-term health effects such as eye, nose, throat and lung irritation and coughing, sneezing, runny nose, and shortness of breath.	Acceptable < 35 μg/m^3 [31] High performance $PM_{2.5}$ < 12 μg/m^3 [31]	Yes

	Particulates within the lungs may cause lung disease, emphysema, and/or lung cancer [29].	
O_3	Found in offices in the presence of photocopiers, laser printers, or any electrical appliances that are poorly maintained.	No
Dust, dirt and moisture	Present especially if the open-plan office contains communal area spaces.	N/A
Odour	generated as part of metabolism and emitted from furnishings and fabrics and bioeffluents.	N/A

[a] 15 minutes average

[b] The threshold is met for a project located where the annual average ambient $PM_{2.5}$ level is 35 μg/m^3 or higher.

Tab. 2 – CONTAM input data.

Contaminant	Initial concentration	Generation rate	Schedule
CO_2	400 ppm	0.0052 L/s	8:00 - 18:00
CH_2O	0	1.0×10-9 kg/s	Always
$PM_{2.5}$[a]	0	0.1 1/h	Always
		1.7 mg/h	8:00 - 18:00

[a] The default value of $PM_{2.5}$ was set to zero as observed from the monitored data. Two models were defined, a decomposition rate of 1/h and a constant coefficient model of 1.7mg/h for printing.

2.3 Contaminants

The air quality at Loughborough UK is categorised as 'fair', meaning that the air quality is generally acceptable for most individuals. However, sensitive groups may experience minor to moderate symptoms from long-term exposure [32].

As for the IAQ in offices, the indoor sources of air pollution are usually carpets, furniture, HVAC and people. Some of the key pollutants found in offices are listed in Tab. 1, including their source and impact on health.

The air parameters and pollutants measured and assessed in this study were T_a, RH, CO_2, CH_2O and $PM_{2.5}$. As for the simulated scenarios, the pollutants defined were CO_2, CH_2O and $PM_{2.5}$. The 'threshold limit value' (TLV) of each pollutant assessed in this study are listed in Tab. 1. Also, the input requirements of each pollutant in the simulations are defined in Tab. 2.

3. Results and Discussion

The simulation results show that the average CO_2 levels in the MV were better than NV by only 10%. That is because higher ventilation rates were achieved in MV than in NV. In both scenarios, the CO_2 levels did not exceed 610 ppm. Comparing the CO_2 simulated results with the real-time measurements, the maximum CO_2 level reached was 530 ppm. The average $PM_{2.5}$ was twofold better under NV than MV, as well as CH_2O was also better under NV than MV by 26% in the simulated scenarios.

The CO_2 and CH_2O levels did not exceed or even reach the TLV in the MV scenario due to the ventilation rate associated with the presence of the occupants. However, $PM_{2.5}$ levels reached 55 μg/m^3 in the MV scenario as subject to the office equipment schedule and were above the acceptable limit for all working hours (50 hours, which is the working hours at the open-plan office per week). In the real-time measurements, the $PM_{2.5}$ reached 43 μg/m^3 and exceeded the acceptable level by only 4 hours for the entire week.

CH_2O and $PM_{2.5}$ levels were better in NV because the vents were open all day long, whereas, in the MV, the air handling unit was operating during the occupied hours only. An additional scenario was performed, including a control schedule for the windows in the NV scenario. The windows were scheduled to open only during occupied hours. As a result, CO_2 and $PM_{2.5}$ levels took more time to dilute and drop to the default concentrations. However, the CH_2O levels increased significantly by 14 times due to the defined constant generation rate of 1.0 $\times 10^{-9}$ kg/(m_2·s). Therefore, the trend in the simulated data for CO_2 and $PM_{2.5}$ varied according to the defined occupancy schedule. Unlike CH_2O, which was defined to be generated at a constant rate based on the office area for all times. Besides, lower ventilation rates were achieved in the NV scenarios as the wind direction was not towards the office openings for that week.

Comparing the real-time measurements and the MV-base case simulation results, the CO_2 levels appeared to be better by 1.4% in the simulation scenario. However, the average $PM_{2.5}$ levels from the real-time measurements were better than the simulated scenario by 39%. Also, when comparing the ambient levels of $PM_{2.5}$ with the simulated results, the ambient levels of $PM_{2.5}$ were better by 48%. The ambient $PM_{2.5}$ were also better than the real-time measurements by 41%. However, the real-time measurements and the ambient $PM_{2.5}$ levels appear to be highly correlated with R^2= 0.34. As for the CH_2O levels, the measured values were much higher than the MV base-case scenario. The measured data exceeded the TLV [26] by 16 hours during the working hours.

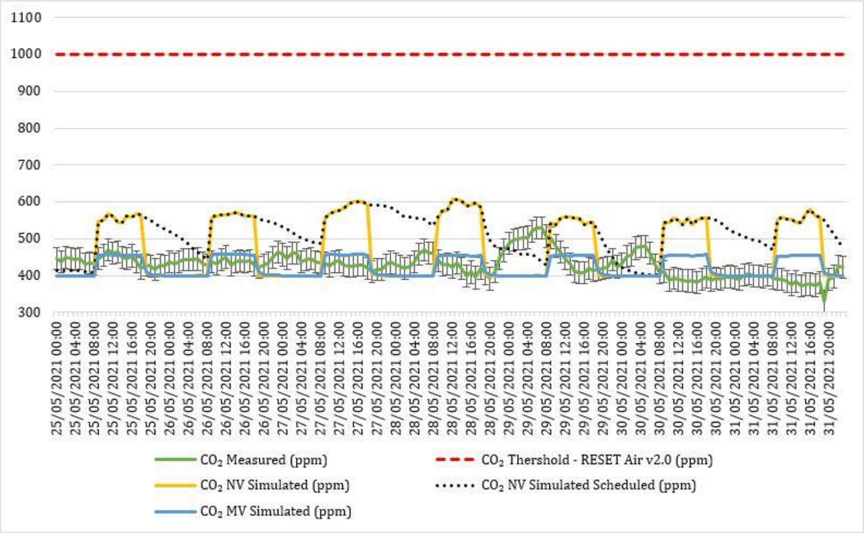

Fig. 2 - Measured and simulated CO_2 in the open-plan office and the acceptable threshold.

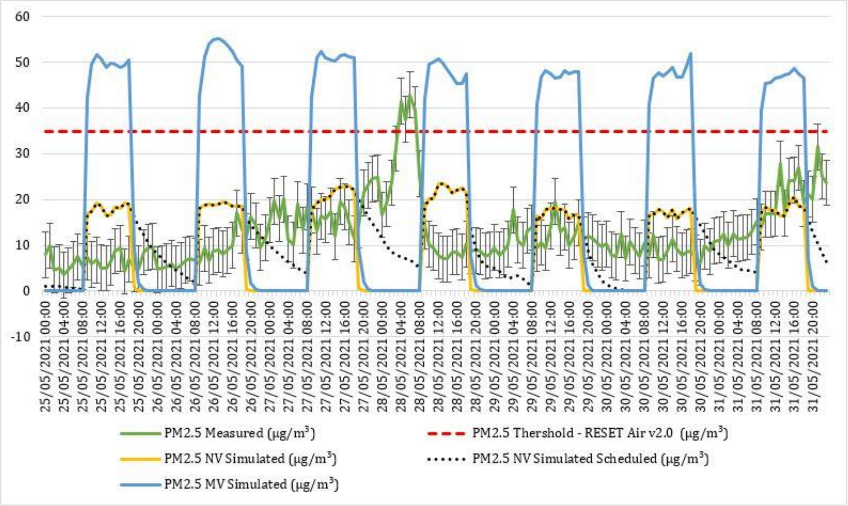

Fig. 3 – Measured and simulated $PM_{2.5}$ in the open-plan office and the acceptable threshold.

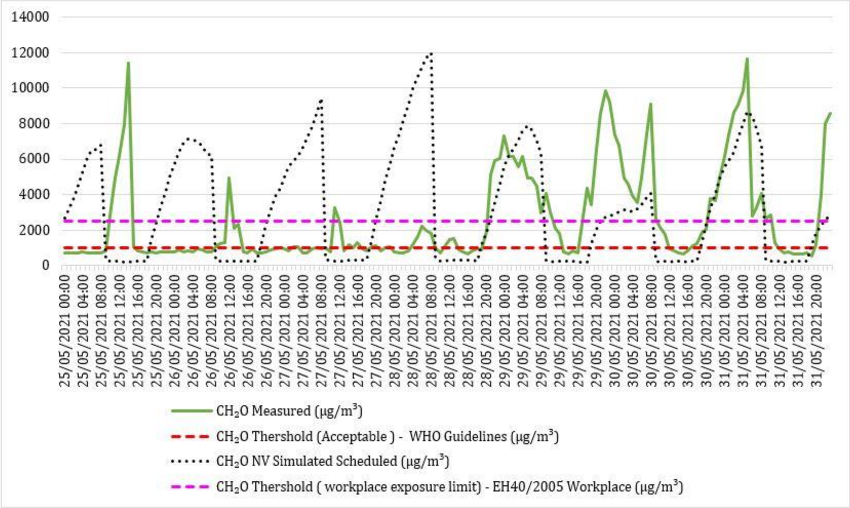

Fig. 4 - Measured and simulated CH2O (NV scheduled scenario) in the open-plan office and the acceptable threshold.

The simulation results of the MV scenario for CO_2 and the real-time measurements reveal that the office was overly ventilated. Although the open-plan office was simulated for full occupancy for the simulation scenarios, and during the measuring period, the occupancy rate was unknown. The office was never at full capacity during the measuring period due to the COVID-19 safety measures taken in the office. Due to the relatively small difference between the simulation results and the real-time measurements, it could be anticipated that if the open-plan office was fully occupied and all office equipment was operating in the real scenario, the CO_2 levels would have been higher than what the simulation results revealed. It is fair to assume that the current ventilation rate in the office is not suitable for full occupancy.

Also, the simulated results for $PM_{2.5}$ levels concluded that in the real case scenario, when the office is fully occupied, and all office equipment is operating, the $PM_{2.5}$ will exceed the TLV for all times as appeared in the MV simulation results. Again, the measured $PM_{2.5}$ has exceeded the TLV only by four hours. However, the office was not fully occupied, and the equipment was not in full use. It is fair to assume that the density of occupants and their operating accompanying office equipment is not suitable for the office area.

As for the CH_2O levels, the measured data shows that the defined generation rate in the simulations was minimal. The trend in the measured confirms that CH_2O levels do increase with the presence of occupants and operating office equipment.

Both the field measurements and simulation results prove that diagnosing and classifying the IAQ of enclosed space based on the analysis of one pollutant is not enough. For instance, the real-time measured data ranks the ventilation and IAQ standard in the open-plan office as 'high' in terms of CO_2, referring to Table 4.1 in CIBSE Guide A, Chapter 4 [5]. Also, the measured data of CO_2 and simulation results reveal that the open-plan office is overly ventilated in terms of CO_2. However, the real-measured data and simulation results indicate that the open-plan office is marginally under-ventilated in terms of CH_2O and $PM_{2.5}$. Measurements of CO_2 levels in indoor spaces effectively identify poor ventilation in high occupancy spaces. However, in low occupancy or large volume spaces, low levels of CO_2 do not necessarily indicate good ventilation.

As for the other comfort conditions in the open-plan office, the measured indoor Ta and RH office were in the comfort range.

4. Conclusion

This study provides results from field measurements compared with simulation results that assess the IAQ under MV and NV ventilation systems of an open-plan office. Overall, this study's results demonstrate the need to diagnose the IAQ of open-plan offices by assessing different pollutants that are likely to be found in the environment. The pollutants measured and assessed in this study were all dominant in the open-plan office. The real-time measured data revealed that the open-plan office is overly ventilated in terms of CO_2 but marginally under-ventilated in terms of CH_2O and $PM_{2.5}$.

Besides, the simulation results for this study revealed that both MV and NV could achieve acceptable IAQ for this specific case study and location (with the existing location of the supply and extract and layout of the office). However, the ventilation control strategy is the manipulator of jeopardising the IAQ in the space. The study confirmed that it is important for the open-plan office to remain ventilated during unoccupied hours under a reasonable control schedule to dilute any pollutants reaching the TLV and control other sources of pollutants, e.g., CH_2O and $PM_{2.5}$ from furniture and electrical equipment. Yet, a trade-off between the IAQ, thermal comfort and energy consumption should be achieved, especially during wintertime, to avoid creating an uncomfortable thermal environment and resulting in higher energy consumption.

It is important to diagnose the indoor air of an enclosed environment to understand the behaviour and trend of the indoor air throughout the seasons and identify the causes of failure of the HVAC system in the building. It is also important to have the number of occupancies known during the evaluation period to assess the indoor pollution associated with the occupancy presence and their activities to indicate the indoor climate quality more accurately. In this study, the measured data provided an understanding of the current ventilation operational status verifying the need to adjust the setpoints as higher ventilation is required for full occupancy for the real case scenario. As in the established guidelines to control COVID-19 indoors, such as in the '*CIBSE COVID-19 Ventilation Guide*' [33], a higher ventilation rate with 100% fresh air is necessary at all times.

Ventilation is the foundation of a healthy building and the most appropriate means of control to replace and dilute the heat, moisture, and gaseous and particulate pollutants that eventually build up indoors. For future studies, a more detailed IAQ analysis will be required. It is recommended that CFD is to be used instead of multizonal analysis (which is based on the well-mixed assumption) to give a detailed pollution profile across the office and demonstrate the movement of pollutants and viruses throughout enclosed spaces. Also, energy analysis is recommended to compare the energy consumption in a building to the corresponding indoor climate comfort conditions. The results can be used to understand the trade-offs of energy and indoor air pollution.

5. Appendices

Tab.3 – An overview of the accuracy of the measurements using the EnLink IAQ sensor

Type	Accuracy	
RF Transmit power Up to +18dBm	Ta	Accuracy: ±0.2°C
	RH	Accuracy: ±2%
	CO_2	Accuracy: ± (30, +3%) ppm
	CH_2O	± 15%
	$PM_{2.5}$	0 μg/m^3 to 100 μg/m^3 ± 10 μg/m^3 100 μg/m^3 to 1000 μg/m^3 ±10 % m.v.

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