The effect of the ventilation retrofit in a school on CO_2, airborne particles, and energy consumptions

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Abstract

The energy retrofit of existing buildings is a key strategy to reduce the energy costs of the building sector. Amongst the retrofit solutions, the adoption of mechanical ventilation systems represents a necessary approach for buildings with high crowding index, such as schools.
The air quality in schools is a main issue since children spend a significant fraction of the year in such microenvironments. To date, the scientific literature has carried out several studies concerning the air quality in naturally ventilated schools worldwide, nonetheless most of the studies performed a general evaluation of the air quality just using the CO_2 as a comprehensive indicator. This is an oversimplified approach since the indoor air quality is affected by several pollutants, including airborne particles, whose behavior cannot be predicted by the CO_2 one.
The aim of the research is the evaluation of the effect of the ventilation retrofit in a classroom on different indoor air quality parameters and energy consumption. To this end a mechanical ventilation system with a heat recovery unit was installed in a test-classroom and tests with CO_2-based demand controlled ventilation were performed. CO_2 levels and indoor-to-outdoor particle concentrations were measured and compared to the pre-retrofit ventilation conditions (i.e. manual airing procedures).
Results showed that mechanical ventilation systems have simultaneous positive effects on the different pollutants investigated as well as on ventilation heat losses: indeed, lower indoor-to-outdoor concentration ratios, with respect to the airing approach, were detected simultaneously for CO_2, sub-micron particles and PM_{10}.

Keywords:

Mechanical ventilation systems; indoor air quality; retrofit; schools; airborne particles; CO_2

1. Introduction

The energy performance of buildings represents one of the main technical goal in building construction and reconstruction activities. Indeed, the building sector accounted for roughly 40% of the EU-28 total final energy consumption [1]. To this end, with the Energy Performance of Buildings Directive [2], the European Union established specific measures to improve the energy efficiency of buildings and achieve the energy saving targets for 2020. In particular, a key regulation aimed at reducing energy consumption in buildings is the introduction of nearly zero energy buildings (NZEBs) as the new building target [3, 4].

A strategic approach to reduce energy consumption of the building sector is the energy retrofit of the existing buildings: this is even more important in countries, like Italy, where about 70% of the buildings were built before any regulatory indication on building energy efficiency [5-7]. To this end, from 2014, the Italian Ministry of Economic Development is compelled to renovate each year at least 3% of the total floor area of heated and/or cooled buildings owned and occupied by the central government [8]. A large percentage (roughly 50%) of such total floor area consists of educational buildings (schools, kindergartens, universities; [9]) whose primary energy consumption is mainly due to heating during cold seasons and hot water production [10]. The Ministry for Education, University and Research recently declared that 58% of Italian school buildings have already taken measures to reduce energy consumptions (www.istruzione.it): the typical energy retrofit interventions adopted are the thermal zoning of the heating plant, the installation of double-glazed windows, installation of solar heating collectors, and insulation of walls, floors and/or ceilings. Nonetheless, the installation of mechanical ventilation systems with heat recovery units does not represent a preferential retrofit solution for school renovation. This is due to the very limited consideration to the indoor air quality issues by the regulatory authorities, indeed they usually prefer put in place policies and incentives supporting energy saving solutions (e.g. renewable energy, building insulation), whereas the improvement of the air quality is considered an energy-consuming technique. The contribution of the ventilation losses in low insulated buildings is lower than the transmission losses, different studies recognized that the heat losses due to the ventilation are roughly 30-40% of the total energy need for space heating [11-13]. These figures clearly explain the reason why the building insulation retrofit has been preferred with respect to the ventilation retrofit. Nonetheless, ventilation losses represent the main cause of energy losses in well insulated buildings [14-16]: this is a key aspect to be handled in view of the design of new or retrofitted low-energy buildings such as NZEBs.

The building ventilation of Italian schools, as well as Italian homes, is usually not properly designed and typically relies upon natural ventilation and manual airing: thus, the indoor air quality depends

on the air leakages of the building and the personal perception of people running the building (i.e. tenants, students, teachers) [17-27]. A number of studies revealed that Italian students can perceive a bad indoor air quality and thermal comfort in naturally ventilated schools [28-31]; such conditions can even worsen when retrofit interventions for building energy efficiency (e.g. window replacement) are applied: indeed, such retrofit solutions reduce the building air permeability and then the natural air exchange rate.

A number of papers were carried out to measure the indoor air quality in schools, nonetheless, most of these studies are mainly focused on CO_2 measurements. Indeed, the CO_2 is unanimously still considered a proxy of the indoor air quality [32, 33] and it is adopted as the key parameter for demand controlled mechanical ventilation (i.e. CO_2-based demand controlled ventilation, [34]) as well as for European standards on indoor air quality [35]. However, the CO_2 behavior cannot be considered representative of all the different pollutants typically present in schools. Its dynamic can be considered representative of the different indoor-generated gaseous pollutants, such as radon and volatile organic compounds (VOCs), but the dynamics and origins of other pollutants produced outdoor and/or in form of particles cannot be predicted by the CO_2 one [23].

Different recent studies paid close attention to airborne particles including both indoor-generated super-micron particles ($PM_{2.5}$, PM_{10}) and outdoor-generated traffic-related sub-micron particles [21, 36-40]. Several papers recognized that high exposure to particles can be measured in schools placed in urban areas and/or close to main roads [37, 41-44]. Such high exposure lead to not negligible contribution of the school-time to the daily dose of particle received by children and, then, to health risks and effects higher than the acceptable levels [25, 37, 45, 46]. In schools with no mechanical ventilation systems, such particle metrics cannot be likely reduced adopting the strategies typically effective for indoor-generated gas-phase pollutants, e.g. increasing the air exchange rate through manual airing. Therefore, in order to simultaneously decrease the energy losses, improve the thermal comfort, and reduce the exposure to all the different pollutants, mechanical ventilation systems should be adopted in schools [15, 47-51]. Nonetheless, even if data on the effect of ventilation retrofit on energy losses [52-55] and thermal comfort [56, 57] are already present in the scientific literature, very few data concerning the effect of the mechanical ventilation on the different pollutants in schools are available.

In order to contribute in filling this gap of knowledge, the aim of the present paper is to investigate the possible positive effect of the adoption of a mechanical ventilation system in a classroom on (i) different indoor air quality parameters and (ii) energy consumption with respect to manual airing strategies. To this end a pilot case-study was performed in a test-classroom located in Cassino (Central Italy) where a retrofit of the ventilation method was performed by installing a mechanical

ventilation system equipped with a heat recovery unit: results were compared to pre-retrofit airing solutions. The authors point out that the data here reported can be easily applied to NZEBs since the mechanical ventilation with heat recovery represents the technical solution typically applied in such low energy buildings.

2. Materials and Methods

The indoor air quality monitoring was carried out in the test-classroom both before and after the ventilation retrofit during the heating season. Tests before the retrofit were performed in the classroom, when no ventilation systems were installed, by imposing different scheduled airing procedures performed by manually opening the window. Tests post-retrofit were conducted after the installation of a mechanical ventilation system imposing a certain indoor CO_2 level. The indoor air quality was assessed by measuring the following parameters: indoor and outdoor particle number, PM_{10}, and CO_2 concentrations.

The estimate of the energy need for space heating of the classroom was performed through a heat balance of the classroom for both the pre-retrofit and post-retrofit cases, on the basis of the EN ISO 52016-1:2017 standard [58] adopting the asset rating method [59].

2.1 Description of the test-classroom

The test-classroom belongs to a primary school placed in Cassino (Central Italy). The city was deeply characterized in terms of ambient particle concentrations in our previous papers. In particular, high levels of airborne particles (both in terms of number and mass concentrations, PM_{10}) were measured in colder seasons likely due to the frequent temperature inversion phenomena [60-62]. Particle concentration gradients were measured throughout the city, with statistically larger concentrations along the trafficked street canyons [61, 63, 64]. In particular, in our recent paper Stabile, Massimo, Rizza, D'Apuzzo, Evangelisti, Scungio, Frattolillo, Cortellessa and Buonanno [62] the emission of different pollutants due to the different sources within the city was determined: the study revealed that more than 70% of the total ultrafine particles emitted in the urban came from vehicular traffic, whereas PM_{10} emission was mostly (almost 90%) due to the heating systems of the residential sector. The characterization of the emission sources of the city is a key information since the school under investigation is located in a block of the urban area (Figure 1) close to streets with an average traffic density of 36 ± 2 vehicles min^{-1} with peaks during the rush hours equal to 44 ± 1 at 08:30 and 54 ± 2 at 13:30 [65].

The school (built in 1980s) is a two-story building with total floor area and volume of 3700 m^2 and 13000 m^3, respectively. The test-classroom under investigation is a 11.4 m×5.4 m×2.9 m room

(floor surface 61.6 m^2, volume 178.5 m^3), it is placed at ground floor and it is roofed by a terrace. It has two single-glazed aluminum inward opening doors on the longest walls of the classroom: one (2.7×2.6 m) facing east and the other one (5.4×2.6 m) facing west. The east wall of the test-classroom is partly adjacent to another classroom (for 5 m out of 11.4 m), the west and south walls face outdoors, whereas the south wall faces the main corridor of the school (Figure 1). The stratigraphy of the outer walls is made up of an inner layer of lime/gypsum plaster, concrete and hollow clay bricks, and an outer layer of lime/gypsum plaster (thermal transmittance U equal to 0.72 W m^{-2} K^{-1}). The floor is made up a concrete slab and concrete bricks (U=1.10 W m^{-2} K^{-1}), whereas the roof is made up of a concrete slab, a waterproof coat, and ceramic tiles (U=0.99 W m^{-2} K^{-1}). The abovementioned U values were evaluated on the basis of the methodology reported in the ISO 6946 standard [66] and in our previous paper [67]. A not negligible shading effect on the classroom due to the presence of close trees and buildings was also recognized and considered in the classroom heat balance hereinafter reported.

During the experimental analyses the classroom was frequented by 25-27 students. As regard the possible particle emission sources, it's noteworthy to highlight that the classroom is equipped with a chalkboard and that no food preparation activities (neither in the classroom nor in the remaining rooms of the school) were performed. Moreover, other important ultrafine particle sources, such as laser printing [68], combustion sources and smoking activities (including electronic cigarette use) [69-71], are not performed in the school. The teaching activities in the test-classroom start at 8:30 and end at 13:00, a 15-min break (usually spent inside the classroom) is scheduled around 10:30.

2.2 Experimental apparatus for air quality measurements

The following instruments were used to measure the indoor and outdoor pollutant concentrations:

- two diffusion Charger Particle Counters (Testo DiSCmini) which are able to measure the total particle number concentration in the 10-700 nm size range based on the electrical charging of the aerosol with 1-s time resolution;
- two DustTrak™ DRX Aerosol Monitors (Model 8534, TSI Incorporated, St. Paul, MN, USA) which are able to measure PM_{10} concentrations on the basis of a light scattering technique with 1-s time resolution;
- a non-dispersive infrared analyzer (Testo - Ambient CO_2 probe; CO_2 concentration range: 0–10000 ppm), connected to a Testo 435-4 Datalogger, to measure temperature, humidity, CO_2 and pressure with 1-s time resolution;

- a non-dispersive infrared sensor, TSI Model 7515 IAQ-CALC™ (TSI Incorporated, Shoreview, MN, USA; CO_2 concentration range: 0–5000 ppm), to measure CO_2 concentration with 1-s time resolution;
- two hot wire anemometers (Testo 0635 1025; Probe head diameter: 7.5 mm, measuring range: 0-20 m s^{-1}), connected to Testo 435-4 Dataloggers, able to measure velocity and temperature of the flow rate in the ducts (used for mechanical ventilation tests) with 1-s time resolution;
- two pairs of 4 wires thermoplastic magnetic contacts mounted on windows and doors and connected to a multimeter to detect opening and closing periods of windows/doors with 1-s time resolution.

The DiscMinis and DustTraks were calibrated (in terms of particle number and mass concentration, respectively) in the European Accredited Laboratory at the University of Cassino and Southern Lazio. In particular, the DiscMinis were compared to a TSI 3068B Aerosol Electrometer [72, 73], whereas the DustTraks were compared to the gravimetric method [74, 75] at the beginning of experimental campaign. Moreover, before each measurement, a further comparison between the two DiscMinis and the two DustTraks was performed in order to take into account for the possible on-field effects on the hand-held instruments (e.g. the specific aerosol under investigation) and for unexpected instrument drift.

The instrumentations used in the classroom (one DiscMini, one DustTrak and the Testo - Ambient CO_2 probe) were placed on a 0.8 m-tall desk above the ground, away from blackboard and in proximity of the student seating area. The instruments outside the classroom (one DiscMini, one DustTrak) were placed on a 0.8 m-tall desk above the ground outside the openable window (within 2 m from the window) in order to properly measure the indoor-to-outdoor concentration ratios (Figure 1). All of the instruments used in the experimental campaign at schools were connected to main power and operated during school hours. Data were post-processed considering 1-min average values.

2.3 Pre-retrofit testing: manual airing tests

Pre-retrofit testing of the indoor air quality in the test-classroom was performed on February–March 2016 by imposing scheduled airing procedures. During the airing tests the window facing the west side was locked, therefore, the air exchange rate relied upon the opening periods of the east-facing window. Such window has one 0.90×2.6 m openable shutter, whereas the other shutters were kept close. This window opening approach was adopted since, on the basis of the teachers' experience, this is the usual scenario in the operation of the classroom. In order to monitor scheduled or

additional window and door openings, both on the door and the east-facing window were installed 4 wires thermoplastic magnetic contacts connected to a multimeter to detect opening and closing periods of window/door.

The evaluation of the manual airing strategy on indoor air quality was performed through four different tests during which the manual airing of the classroom was realized opening the window for 5, 10, 15 or 20 min every hour, respectively. The airing procedure was done by the teachers, they were asked to open the shutter wide. The door was not used for airing purpose but just to allow people entering and exiting the classroom (just quick openings). Nonetheless, the imposed scheduled opening periods were also checked *a-posteriori* analyzing the magnetic contact data stored by the multimeter. Further details on the experimental analysis regarding manual airing tests are reported in our previous paper Stabile, Dell'Isola, Russi, Massimo and Buonanno [23]. As an example, outdoor meteo-climatic data are provided therein. In particular, wind speed and direction data, which can affect the pollutant infiltration and exfiltration during manual airing, are reported: very low wind velocities (equal or less than 0.1 m s^{-1}) with no prevailing directions were detected for the airing tests 10, 15, and 20 min h^{-1}, whereas no data are available for the 5 min h^{-1} test.

2.3.1 Air exchange measurements

In order to provide a comprehensive information about the overall fresh air entering the room during the total school-time day, the air exchange rate of the airing tests was estimated. In particular, a weighted average of the air exchange rates typical of window close configuration (n_{wc}) and window open configuration (n_{wo}) was estimated as:

$$n_{airing} = (n_{wc} \cdot t_{wc} + n_{wo} \cdot t_{wo})/(t_{wc} + t_{wo}) \quad (1)$$

where t_{wc} and t_{wo} represent the total time during which the windows were kept closed (*wc*) and open (*wo*), respectively; the sum of t_{wc} and t_{wo} clearly represents the overall school time (8.30 - 13.00, i.e. 270 min). The air exchange rates n_{wc} and n_{wo} were evaluated through *ad-hoc* CO_2 decay tests (ISO 12569:2017; International Organization for Standardization [76]): in particular, CO_2 concentration decay in the classroom were measured as soon as the students left the classrooms for about 1 h. 10 measurements were performed with doors and windows closed in order to evaluate the air exchange rate of the classroom due to the room leakages solely (n_{wc}), and 10 measurements were carried out with windows open to evaluate the air exchange rate due to the window manual airing (n_{wc}), as also applied in previous papers by Bekö, Gustavsen, Frederiksen, Bergsøe, Kolarik, Gunnarsen, Toftum and Clausen [77], Howard-Reed, Wallace and Ott [78], Biler, Unlu Tavil, Su and Khan [79], Wallace, Emmerich and Howard-Reed [80]. Measuring the CO_2 decay after school activities guarantees high and homogeneous CO_2 concentrations inside the room. CO_2 concentration

measurements were performed through the Testo-Ambient CO_2 probe. Since CO_2 concentration in the room is uniform and no chemical reaction between the gas and other chemicals are expected, the air exchange rate of the room (n) can be determined according the exponential decay equation [81]:

$$n = \frac{1}{\Delta t} \cdot \ln \frac{CO_{2-peak} - CO_{2-out}}{CO_{2-final} - CO_{2-out}} \quad (h^{-1}) \quad (2)$$

where $CO_{2\text{-peak}}$, $CO_{2\text{-final}}$ and $CO_{2\text{-out}}$ represent the peak, final and outdoor CO_2 concentrations and Δt the time interval between $CO_{2\text{-peak}}$ and $CO_{2\text{-final}}$. Outdoor CO_2 concentrations were measured before and after the decay test through the TSI Model 7515 IAQ-CALC^{TM}: $CO_{2\text{-out}}$ here used represents the average value. The authors highlight that the air exchange rate of indoor environments can be affected by the indoor-to-outdoor temperature difference, in particular, higher temperature differences can increase the air exchange rate [80]. Therefore, the air exchange rates measured with no students in the classroom, i.e. with a lower heat load, could be slightly underestimated with respect to the school-time value. Nonetheless, to a first approximation, such possible underestimate could be considered negligible since (i) outdoor temperatures are typical higher on the school end time and (ii) the heating system is still working after the school end time (other extracurricular activities are typically performed in the classroom after lunch).

2.4 Post-retrofit testing: mechanical ventilation tests

The ventilation retrofit of the test-classroom was performed by installing two controlled mechanical ventilation units for ceiling installation equipped with a heat recovery unit (Figure 2). Each unit has a maximum nominal air flow of 500 $m^3\ h^{-1}$, a useful static pressure of 80 Pa, two G4 filters (to filter both the exhaust air from inside to outside and the fresh air from outside to inside), two fans with a maximum velocity of 3200 rpm, and a heat recovery unit with a nominal winter efficiency of 87% at 500 $m^3\ h^{-1}$ and 92% at 250 $m^3\ h^{-1}$.

Each unit was connected to a CO_2 wireless controller allowing to perform a CO_2-based demand controlled ventilation: indeed, the controller is able to detect the CO_2 level in the classroom and adjust the ventilation unit flow rates in order to guarantee a CO_2 concentration below the set-point. To this purpose, the ventilation unit has a multi-speed drive system, it is able to adjust its fan speed amongst three set flow rates: in the present experimental analysis the three fan speeds set were 20%, 40% and 60% of the maximum nominal air flow with a power consumption of 28, 67, and 83 W, respectively. The CO_2 wireless controller were installed on a wall at a height of 1.5 m.

The outdoor fresh air entering the ventilation units passes through a heat recovery section where is heated by the warm exhaust air expelled from indoor to outdoor. The fresh air is then diffused in the classroom through *ad-hoc* micro-perforated ducts (20 cm in diameter) whose nozzle geometry and size were designed to guarantee a homogeneous air diffusion in the room (Figure 2). Indeed, the

two ducts for air diffusion were installed at one fourth and three fourth of the longest side of the room in order to increase the efficiency of the air exchange and reduce the age of air in each point of the classroom. The ducts (20 cm in diameter) connected to the ventilation units to sample the fresh air from outside and to eject the exhaust air from inside to outside were passed through the window glaze by means of 20-cm holes; after the installation, silicone was used to seal possible leakages between the ducts and the window glazes in order to avoid adding further leakages to the classroom envelope.

The fresh air flow rate was calculated on the basis of air velocity measurement performed through the two hot wire anemometers at the center of the ducts (i.e. maximum velocity).

Five tests with the mechanical ventilation system in operation were performed on February 2018; in particular, CO_2-based demand-controlled ventilation tests were carried out by setting the control system at a CO_2 level of 1000 ppm. The average air exchange rates of the mechanical ventilation tests were easily evaluated by dividing the school time average fresh air flow rate by the volume of the classroom.

Two further tests were carried out on February 2019 just to check the energy efficiency of the recovery unit. In particular, the tests were carried out on one of two ventilation units. To this end, one anemometer was installed on duct sampling fresh air from outside ($T_{outdoor}$, i.e. same measurement point of the abovementioned test), whereas the other anemometer was installed in the duct injecting the fresh air (T_{supply_air}) in the classroom (at the exit of the unit, then just upstream of the micro-perforated duct section). Finally, the Testo Ambient CO_2 probe was placed in the classroom to measure the indoor temperature (T_{indoor}). The energy efficiency of the recovery unit (η_{RU}) was calculated considering the median values of $T_{outdoor}$, T_{supply_air}, and T_{indoor} during the school time as:

$$\eta_{RU} = \frac{T_{supply\_air} - T_{outdoor}}{T_{indoor} - T_{outdoor}} \quad (3)$$

Energy efficiencies on the two measurement days were calculated equal to 90.8% ($T_{outdoor}$=9.7 °C, T_{supply_air}=19.6 °C, T_{indoor}=20.6 °C) and 92.4% ($T_{outdoor}$=11.6 °C, T_{supply_air}=19.5 °C, T_{indoor}=20.2 °C), then confirming the high energy efficiency value provided by the manufacturer. To this end, the energy consumptions (section 2.5) of the classrooms were evaluated considering the nominal efficiency (90%).

2.5 Energy need for space heating

In order to evaluate the contribution of the ventilation heat losses on the overall energy needs for space heating of the classroom, a steady-state heat balance of the test-classroom was performed for both the pre-retrofit and post-retrofit cases on the basis of the EN ISO 52016-1:2017 standard [58].

The calculation of the energy needs for space heating of the classroom was performed adopting the asset rating method and considering a monthly calculation procedure [59], i.e. considering standard use of the building (24 h for all the heating season) and standard values for climate data (monthly averaged outdoor temperatures and a 20 °C set point for the indoor temperature). The heating season for Cassino lasts 136 days (November 15th – March 31st) as defined by the Decreto del Presidente della Repubblica 412/1993 [82], indeed the city requires 1164 heating degree days [83]. The energy need for space heating ($Q_{H,nd}$) was calculated as [58]:

$$Q_{H,nd} = Q_{H,tr} + Q_{H,ve} - \eta_{H,gn}(Q_{int} + Q_{sol}) \quad \text{(MJ)} \quad (4)$$

where $Q_{H,tr}$ and $Q_{H,ve}$ are the transmission and ventilation heat transfers, respectively, Q_{int} and Q_{sol} represent the internal and solar total heat gains, respectively, and $\eta_{H,gn}$ is the dimensionless gain utilization factor. Q_{int}, Q_{sol}, and $\eta_{H,gn}$ were evaluated according to the EN ISO 52016-1:2017 standard [58] considering a nominal occupancy of 28 persons and taking into account for the site specific shading effects. The transmission heat transfer $Q_{H,tr}$ takes into account for the heat losses through the building envelope including walls facing outdoor or adjacent unconditioned rooms, windows, thermal bridges, floor and roof. For the sake of brevity, here is just reported the general equation to calculate $Q_{H,tr}$ (EN ISO 52016-1:2017 standard [58]):

$$Q_{H,tr} = \sum_i H_{tr,adj}(\theta_{int,set,H} - \theta_{e,i})t_i \quad \text{(MJ)} \quad (5)$$

where $H_{tr,adj}$ is the overall heat transfer coefficient by transmission (W K^{-1}) of the classroom, $\theta_{int,set,H}$ is the indoor set-point temperature of the for heating (°C) [6], θ_e is the temperature of the external environment of the i-th month of the heating season (°C), and t is the duration of the calculation step (s).

The ventilation heat transfer ($Q_{H,ve}$) is evaluated as:

$$Q_{H,ve} = \sum_i H_{ve,adj}(\theta_{int,set,H} - \theta_{e,i})t_i = \sum_i V \cdot n \cdot \rho_a \cdot c_a(\theta_{int,set,H} - \theta_{e,i})t_i \quad \text{(MJ)} \quad (6)$$

where V is the room volume, c_p is the specific heat capacity at constant pressure (1.01 kJ kg^{-1} K^{-1}), ρ is the air density (calculated at 20 °C, 1.2 kg m^{-3}), and n is the air exchange rate.

The air exchange rate value was evaluated according to different ventilation scenarios tested. First of all, the required ventilation according to the current standards was determined on the basis of the EN 15251 standard [35] considering the "method based on ventilation rate per person or per floor area". In particular, the building category III in terms of required indoor air quality was considered (it represents the value suggested for existing buildings): thus, the n value was evaluated using an airflow per person of 4 L s^{-1} person^{-1} and an airflow for building emissions pollutions 0.4 L s^{-1} m^{-2} (value suggested for low polluting buildings). The resulting air exchange rate was 2.76 h^{-1} (i.e. 4.88 L s^{-1} person^{-1}). Ventilation heat transfer values were then calculated considering the air exchange

rates estimated for the different manual airing tests (n_{airing}; section 2.3.1) and mechanical ventilation tests (section 2.4). As regard the mechanical ventilation scenario, a nominal energy efficiency of the recovery unit equal to 90% was considered on the basis of the ventilation unit datasheet (confirmed by the experimental analysis described in section 2.4). The additional power consumption for the fans was added to ventilation heat transfer term ($Q_{H,ve}$). Such consumption was evaluated considering a standard use of the building (24 h for all the heating season).

3. Results

3.1 Pre-retrofit results: airing tests

The median air exchange rates measured for CO_2 decay tests with windows closed (n_{wc}) and open (n_{wo}) were measured equal to 0.22 h^{-1} (0.18-0.26 h^{-1}) and 3.77 h^{-1} (2.99-4.88 h^{-1}), respectively. The measured n_{wc} value is similar to the air exchange rate data measured with windows closed in Italian classrooms [24]; similarly, a n_{wo} of roughly 3 h^{-1} was measured by Wallace, Emmerich and Howard-Reed [80] in their tests performed with windows open. On the basis of the measured n_{wc} and n_{wo} values and of the weighted average air exchange rate equation (eq. 1) described in the Methodology section, the air exchange rates of tests performed with different airing periods (n_{airing}) were estimated and summarized in Table 1. The median n_{airing} were equal to 0.48, 0.75, 1.01, and 1.27 h^{-1} for airing periods of 5, 10, 15, and 20 min h^{-1}, respectively. Considering a nominal occupancy of 28 persons (27 students, 1 teacher) the corresponding median personal ventilation rates resulted equal to 0.86, 1.32, 1.79, and 2.25 L s^{-1} per person for airing periods of 5, 10, 15, and 20 min h^{-1}, respectively: these data are lower than the minimum required value calculated, according the European EN 15251 standard [35], equal to 4.88 L s^{-1} $person^{-1}$. Such low personal ventilation rates resulted not appropriate to guarantee adequate indoor CO_2 concentrations as hereinafter reported; moreover, median indoor temperature values resulted larger than the design values defined by the Decreto del Presidente della Repubblica 412/1993 [82]. The authors highlight that the effect of the classroom overheating on children wellbeing and performance is a research aspect still under investigation by the scientific literature [38, 84, 85] and it is beyond the aim of the present paper. Indeed, the energy consumptions were carried out considering the standard indoor temperature values (20 °C as set point; asset rating method).

The heat balance on the test-classroom carried out on the basis of the methodology described in the section 2.5 revealed a total energy need for heat space of the classroom ranging from 44.1×10^3 to 50.5×10^3 MJ depending on the ventilation heat transfer ($Q_{H,ve}$) and, then, on the air exchange rates estimated for the different airing tests. $Q_{H,tr}$, Q_{int} and Q_{sol} were equal to 45.0×10^3 MJ, 2.91×10^3 MJ,

and 2.03×10^3 MJ, respectively, whereas, the $Q_{H,ve}$ ranged from 3.94×10^3 to 10.4×10^3 MJ, i.e. from 9% to 21% of the total energy need. Nonetheless, as mentioned above, such $Q_{H,ve}$ values were obtained adopting air exchange rates much lower than required one. Guaranteeing the minimum n value imposed by the EN 15251 standard (i.e. 2.76 h^{-1}) just through the manual airing procedures would cause a ventilation heat transfer of 22.5×10^3 MJ and a total energy need for heat space equal to 62.6×10^3 MJ; in this case the relative contribution of the ventilation itself would raise up to 36%.

In Figure 3 the CO_2 trends measured in the classroom during the different manual airing tests are reported. Typical CO_2 exponential growths and decays were measured during the periods with windows closed and open, respectively. As expected, the longer the airing period the lower the daily-average CO_2 concentrations. As an example, during 5 min h^{-1} airing period test the occupants decided to open the door for roughly 20 min as they perceived a poor indoor air quality. The statistics of the CO_2 values measured during the airing tests are reported in Figure 4 and Table 1: median CO_2 values were equal to 1756, 1482, 1310, and 1085 ppm for airing periods of 5, 10, 15, and 20 min h^{-1}, respectively. The Kruskal-Wallis rank test applied to the four CO_2 trends confirmed that the CO_2 levels measured applying the four different airing procedures resulted statistically different ($p<0.01$), then demonstrating that a properly scheduled manual airing procedure can positively affect the CO_2 levels in classroom. Outdoor CO_2 average values resulted lower than 600 ppm.

Nonetheless, the positive effect of longer airing periods on CO_2 resulted in a negative effect on outdoor-generated pollutants, such as airborne particles. As an example, in Figure 5 the trends of CO_2, particle number and PM_{10} concentrations measured during the school time for the test with an airing procedure of 20 min h^{-1} are reported. The Figure 5a clearly shows that the particle number concentration (which is the metrics typical of outdoor-generated sub-micron particles) is higher outdoor than indoor since no indoor combustion sources are present and the building has a particle penetration factor lower than one. Nonetheless, during the airing periods the indoor particle number concentration approaches to the outdoor one: therefore, for longer airing period, i.e. for higher air exchange rate (n_{airing}) a greater particle penetration factor is expected. This phenomenon is summarized in the Figure 6a where the statistics of the particle number concentrations measured both indoor and outdoor for the different airing tests are reported. The Kruskal-Wallis rank test applied to indoor and outdoor particle number concentration trends confirmed that the outdoor concentrations are statistically higher ($p<0.01$) than indoor ones; nonetheless, moving from 5 min h^{-1} to 20 min h^{-1} airing test, the median indoor concentrations come nearer to the outdoor ones: this leads to an increase of the median indoor-to-outdoor particle number concentration ratio from 0.57 (5 min h^{-1} airing test) to 0.80 (20 min h^{-1} airing test) as highlighted in Figure 7.

A completely different behavior was recognized for PM_{10} which represents the airborne particle metrics typical of super-micron particles. In fact, PM_{10} trends reported in Figure 5b highlight that the indoor PM_{10} concentration is higher than the outdoor one; this is likely due to the indoor emission of super-micron particles coming from resuspension processes (mainly occurring during breaks) and chalk use [45]. Therefore, the indoor PM_{10} levels are mostly influenced by indoor-generated super-micron particles with respect to the penetration from outdoor. In Figure 6b the statistics of the PM_{10} concentrations measured both indoor and outdoor for the different airing tests are summarized, the box-plots confirmed that the indoor PM_{10} levels were statistically higher than the outdoor ones (Kruskal-Wallis rank test, $p<0.01$) for all the airing test performed; moreover, unlike the sub-micron particles, the effect of the airing period duration is negligible. This is clearly shown in Figure 7 where the median indoor-to-outdoor PM_{10} concentration ratios are reported: the ratios strongly varied (from roughly 2 to 5) and no recognizable correlations where found with the airing period interval.

3.2 Post-retrofit results: mechanical ventilation tests

In Figure 3 the median CO_2 trend (and corresponding minimum and maximum variations) measured in the classroom during the different mechanical ventilation tests are reported. Trends were summarized all together since they resulted statistically similar. The median CO_2 value amongst all the mechanical ventilation tests resulted equal to 1002 ppm, with reduced variation during the school-time due to the CO_2 set point of 1000 ppm which does not allows significant increases of CO_2 levels in the classroom. This is also confirmed by the very narrow box-plot of Figure 4 representing the statistics of all the five mechanical ventilation tests. Exponential CO_2 growths typical of tests with no mechanical ventilation are just limited to the first period of the school time when the air flow rate of the mechanical ventilation units is still too low with respect to the students' CO_2 generation rate. Nonetheless, for higher CO_2 concentrations, the control systems of the ventilation units increase the fan speeds then raising the air exchange flow rate of the classroom: this is clearly recognizable from the data reported in Figure 8 where CO_2, particle number, and PM_{10} concentration trends measured during one of the mechanical ventilation tests are reported. The median CO_2 concentration during the specific test was equal to 963 ppm, indeed, the mechanical ventilation unit control systems varied their flow rate from roughly 150 $m^3\ h^{-1}$ (first fan speed level) to about 440 $m^3\ h^{-1}$ (second fan speed level) resulting in a school-time average air exchange rate for this test equal to 2.33 h^{-1}. The authors point out that all the mechanical ventilation tests were performed considering the same CO_2 set point (1000 ppm) and a quite constant occupancy (which means a roughly constant CO_2 generation rate): this leads to very similar

ventilation rates (ranging from 2.33 to 2.79 h^{-1}; median value of 2.51 h^{-1}) and (as mentioned above) not statistical differences amongst the CO_2 data obtained for the different tests. Moreover, the authors also highlight that the indoor CO_2 level of roughly 1000 ppm was reached with an air exchange rate of 4.43 L s^{-1} per person (considering an occupancy of 28 people), i.e. with a ventilation rate quite close to that suggested by the European EN 15251 standard [35] for "acceptable" air quality targets in existing buildings (4.88 L s^{-1} $person^{-1}$). Outdoor CO_2 average values measured resulted lower than 600 ppm.

Median indoor temperature (21.3 °C, Table 1) during the mechanical ventilation tests resulted within the design values defined by the Italian regulation [82] and slightly lower than those measured during the manual airing tests. Nonetheless, the data here shown are not sufficient to investigate in-depth the effect of the ventilation systems on the indoor thermal comfort. A more uniform temperature during the school time and within the room can be just speculated considering the air distribution system in the room and the increased air exchange rate, but these aspects should be analyzed in further *ad-hoc* researches.

As regard the airborne particle concentrations, the illustrative data shown in Figure 8 demonstrate that the shape of the indoor particle number concentration trend is similar to the outdoor one but the concentrations are much lower. Indeed, since the fresh air entering the room is mostly due to the mechanical ventilation unit and windows were kept close during the tests, the indoor concentration levels cannot approach to the outdoor one (unlike the manual airing tests): the indoor-to-outdoor concentration ratio is barely related to the filtration efficiency of the ventilation unit filters. Such ratio ranged from 0.39 to 0.56 during the mechanical ventilation tests as reported in Figure 7: these values are lower than the manual airing test ones and can be even reduced adopting filters characterized by a higher filtration efficiency for sub-micron particles (e.g. F7 filter).

Finally, the illustrative PM_{10} concentration trends of Figure 8 showed that, even when mechanical ventilation systems are adopted, the indoor PM_{10} concentration is still higher than the outdoor one; in fact, super-micron particle peaks, likely due to resuspension phenomena, are still present. Nonetheless, as reported in Figure 7, the indoor-to-outdoor PM_{10} concentration ratios measured during the mechanical ventilation tests resulted much lower than the manual airing test ones: they ranged from 1.14 to 2.00 with a median value of 1.33. Therefore, the increased air exchange rates typical of the mechanical ventilation tests are able to smooth significantly the super-micron particle peaks related to the indoor emission phenomena. Higher air exchange rates could further reduce the indoor PM_{10} concentrations. The positive effect of the mechanical ventilation in classrooms agrees with the findings of Trompetter, Boulic, Ancelet, Garcia-Ramirez, Davy, Wang and Phipps [86] who recognized a 66% reduction of PM concentrations during school-time in ventilated classrooms

with respect to those not ventilated in their tests performed in New Zealand schools. They also detected that the increased PM in the classrooms was predominantly from crustal sources, i.e. soil tracked in from outside on footwear and re-suspended during activities within the classrooms; whereas the outdoor combustion sources (e.g. traffic) have a minor contribution. On the contrary, PM ratios lower than 1 were detected in residential microenvironments [87] where negligible resuspension phenomena typically occur; in such environments the higher the ventilation rate adopted, the lower the PM indoor-to-outdoor ratio.

As regard the energy need for classroom heating in the post-retrofit configuration, the terms $Q_{H,tr}$, Q_{int} and Q_{sol} were equal to the abovementioned pre-retrofit conditions, whereas the ventilation heat transfer ($Q_{H,ve}$) increases as a function of the increased air exchange rate. Considering the median air exchange rate for mechanical ventilation tests (2.51 h^{-1}), the ventilation heat losses (including the additional power consumption for the fans of 0.71×10^3 MJ) are equal to 21.2×10^3 MJ. Nonetheless, considering a nominal heat recovery efficiency of the ventilation units equal to 90%, the actual ventilation losses are just equal to 2.76×10^3 MJ then leading to a total energy need for space heating of 42.9×10^3 MJ. Therefore, when compared to the ventilation scenario imposed by the standard, the post-retrofit ventilation scenario leads to a median energy save for space heating equal to 32%. The mechanical ventilation solution represents the more convenient approach with respect to other ventilation strategies when the same air exchange rate is considered. In fact, the energy needs for space heating evaluated for airing tests resulted lower (19% to 30%) than the value calculated for the EN 15251 ventilation scenario. Nonetheless, such energy saving of the airing tests is misleading since was obtained not taking into account the air quality issues.

Summarizing, the airing procedure tests and the mechanical ventilation tests performed in the test-classroom under investigation demonstrate a positive effect of such a ventilation retrofit on both (i) the different parameters of the indoor air quality and (ii) the energy consumption for space heating. Indeed, despite the well-known positive effects in terms of thermal comfort (analyzed in previous studies), the results of the proposed research revealed simultaneous positive effects of the mechanical ventilation system on CO_2, particle number and PM_{10} concentrations in classroom, i.e. on (a) indoor-generated gaseous pollutants whose CO_2 is a good proxy (e.g. radon, volatile organic compounds), (b) outdoor-generated traffic-related sub-micron particles and the carried compounds emitted by the vehicles (e.g. black carbon, heavy metals, particle-bound polycyclic aromatic hydrocarbons), (c) indoor-generated super-micron particles. The positive effect of the mechanical ventilation on indoor-generated gaseous pollutants and indoor-generated super-micron particles is merely due to the increased air exchange rate, whereas, the positive effect on outdoor-generated

traffic-related sub-micron particles is related to the reduced penetration of the filtration systems. As regard the indoor-generated gaseous pollutants, the authors point out that the qualitative effect of the different ventilation scenarios on such pollutants is similar since the dynamic of the different gases is similar too. Nonetheless, when it comes to quantitative effects, the indoor concentrations of these pollutants are affected by the emission rates, which can differ significantly amongst the pollutants.

Concerning the outdoor-generated traffic-related sub-micron particles, a further critical aspect regarding the effect of the manual airing on indoor concentrations needs to be pointed out: i.e. the period of the opening time. Due to the significant variation of outdoor particle number concentrations during the school-time, different indoor particle number concentrations could be measured whether the manual airing period is performed at the start or at the end of the hour. As an example, opening the windows at school start time could likely cause higher indoor concentrations due to the high concentrations typical of the rush hour. This aspect was not further analyzed in the paper and could lead to even higher benefit of the mechanical ventilation with respect to the manual airing.

The above-mentioned limitations of the study could raise some issues regarding the transferability of the data here shown. Actually, the authors highlight that the measurement of the pollutant concentration levels is not an aim in itself. Indeed, the main finding of the paper is the effect of the ventilation strategies on the different pollutant concentrations, i.e. the study highlights how the different pollutants can be affected by different ventilation approaches. Nonetheless, different absolute indoor concentrations with respect to the ones here shown are expected in environments characterized by (i) different building envelope airtightness (e.g. different penetration through the windows), (ii) different meteo-climatic conditions, (iii) different emission of CO_2 and PM_{10}, (iv) different outdoor particle number concentrations. Anyway, the same qualitative positive effect is expected when the ventilation of the buildings is improved. Moreover, even if the absolute results are not immediately transferable to other buildings, similar data of particle penetration and CO_2 exfiltration are expected for schools built before regulatory indication on building energy efficiency (the larger fraction of the existing schools) and not yet retrofitted. In fact, in our previous paper [24], we have measured the airtightness of 7 naturally ventilated schools (16 classrooms) placed in the Central Italy, recognizing similar air exchange rates.

4. Conclusions

In the present paper the effect of the ventilation retrofit on the indoor air quality and energy consumption in classrooms was investigated. To this end, pre-retrofit (manual airing) and post-

retrofit (mechanical ventilation system with heat recovery unit) solutions were compared in terms of different air quality parameters and energy consumption for space heating performing *ad-hoc* tests in a test-classroom. In particular, measurements of indoor and outdoor particle number, PM_{10}, and CO_2 concentrations were performed. Pre-retrofit tests were carried out considering different manual airing procedures (by manually opening windows), whereas post-retrofit tests were performed adopting a CO_2-based demand controlled ventilation (set-point of 1000 ppm).

The airing tests showed that statistically significant CO_2 reductions can be achieved when longer airing periods were considered, anyway, this approach leads to higher sub-micron particle infiltration from outdoor: indoor-to-outdoor particle number concentration ratios increase from 0.57 to 0.80 when the estimated air exchange rates raise from 0.48 to 1.27 h^{-1}. On the contrary, no significant reductions were detected for indoor-generated PM_{10} since indoor-to-outdoor ratios (much larger than 1) were poorly correlated to the increased air exchange rates.

Mechanical ventilation tests showed simultaneous positive effects on all the pollutants under investigation as well as on energy saving. Indeed, the CO_2-based demand controlled ventilation was able to guarantee CO_2 levels lower than 1000 ppm; moreover, even if just G4 filters are used, the penetration of sub-micron particles resulted lower than pre-retrofit tests (indoor-to-outdoor particle number concentration ratios equal to 0.39-0.56). Furthermore, super-micron particles were also positively affected by the mechanical ventilation system: indeed, lower indoor-to-outdoor PM_{10} ratios were measured due to the increased dilution caused by the higher air exchange rates. The reduction of the energy consumption for space heating estimated for post-retrofit ventilation scenarios was due to the heat recovery unit of the mechanical ventilation system. In particular, an energy saving of 32% with respect to the required ventilation (if performed by manual airing) imposed by the current standard was estimated considering an asset rating approach.

The preliminary results here shown are very promising since demonstrate the effectiveness of the mechanical ventilation systems on the different types of pollutants. Further analyses could be carried out to provide further information on pollutants not measured in the present study (e.g. NOx and other pollutants emitted by vehicular traffic), thermal comfort, as well as on the effect on the children performance.

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Figure captions

Figure 1 – Maps of the urban area of Cassino: location of the school, the test-classroom and the outdoor sampling site.

Figure 2 – Scheme (not to scale) and picture of the mechanical ventilation units and air distribution ducts installed in the test classroom.

Figure 3 – CO_2 trends measured during the manual airing tests and mechanical ventilation (MV) tests. The five MV test results were expressed as median MV CO_2 trend (and max-min variation) since they resulted not statistical different. The 5 min h^{-1} trend is affected by the unpredicted door opening period occurring on the last school hour. Manual airing trends were already reported in our previous paper Stabile, Dell'Isola, Russi, Massimo and Buonanno [23], please refer to it for further details.

Figure 4 – CO_2 statistics measured during the manual airing tests and mechanical ventilation (MV) tests. The five MV test results were summarized in a single box-plot since they resulted not statistical different. The 5 min h^{-1} data are slightly underestimated due to the unpredicted door opening. Manual airing data were already reported in our previous paper Stabile, Dell'Isola, Russi, Massimo and Buonanno [23], please refer to it for further details.

Figure 5 – Trends of CO_2, particle number (a) and PM_{10} (b) concentrations measured during the school time for the test with an airing procedure of 20 min h^{-1}. Trends were adapted from our previous paper Stabile, Dell'Isola, Russi, Massimo and Buonanno [23], please refer to it for further details.

Figure 6 – Box-plots of particle number (a) and PM_{10} concentrations (b) measured indoor and outdoor during the manual airing tests.

Figure 7 – Indoor-to-outdoor particle number and PM_{10} concentration ratios measured during the manual airing and mechanical ventilation tests.

Figure 8 – Example of mechanical ventilation test: trends of CO_2, particle number (a) and PM_{10} (b) concentrations during the school time measured for one of the five mechanical ventilation tests.

Tables

Table 1 –Air exchange rates, CO2 concentrations, indoor temperature and energy needs of the test-classroom evaluated for the pre-retrofit and post-retrofit ventilation scenarios. Data are reported as median values and corresponding ranges (in brackets).

Ventilation scenarios		n (h^{-1})	Ventilation flow rate (m^3 h^{-1})	Indoor temperature (°C)	CO_2 (ppm)	Ventilation heat transfer, $Q_{H,ve}$ (MJ)	Energy need for space heating, $Q_{H,nd}$ (MJ)	$Q_{H,ve}/Q_{H,nd}$	Energy saving with respect to the EN 15251 (%)
Pre-retrofit	Required by Standard (EN 15251)	2.76	492	20 ± 2 □	-	22.5×10^3*	36%	36%	-
	manual airing; 5 min h^{-1} test	0.48 (0.40-0.59)	86 (71-106)	22.9 (20.1-23.6)	1756 (589-2250)	3.94×10^3 ($3.24\text{-}4.84\times10^3$)	9% (7-11%)	9% (7-11%)	30%*** (28-33%)
	manual airing; 10 min h^{-1} test	0.75 (0.60-0.94)	133 (108-167)	22.9 (19.8-23.7)	1482 (700-2044)	6.09×10^3 ($4.94\text{-}7.64\times10^3$)	13% (11-16%)	13% (11-16%)	26%*** (25-28%)
	manual airing; 15 min h^{-1} test	1.01 (0.81-1.28)	180 (145-228)	23.7 (21.6-24.7)	1310 (710-1791)	8.23×10^3 ($6.63\text{-}10.4\times10^3$)	17% (14-21%)	17% (14-21%)	23%*** (23-24%)
	manual airing; 20 min h^{-1} test	1.27 (1.02-1.62)	227 (182-290)	23.8 (22.4-24.8)	1085 (579-1688)	10.4×10^3 ($8.32\text{-}13.2\times10^3$)	21% (17-25%)	21% (17-25%)	19%*** (19-20%)
Post-retrofit	mechanical ventilation test (heat recovery efficiency=90%**)	2.51 (2.33-2.79)	448 (416-499)	21.3 (20.4-22.3)	1002 (541-1072)	2.76×10^3 ($2.61\text{-}2.99\times10^3$)	6% (6-7%)	6% (6-7%)	32% (29-35%)

□ defined by the Decreto del Presidente della Repubblica 412/1993 [82]
* $Q_{H,ve}$ calculated hypothesizing that the n value imposed by the EN 15251 standard is obtained through the manual airing procedures.
** the heat recovery efficiency was hypothesized on the basis of the ventilation unit datasheet (confirmed by the measurements described in section 2.4).
*** the energy savings here reported are evaluated with respect to the ventilation required by the EN 15251 through manual airing (%)

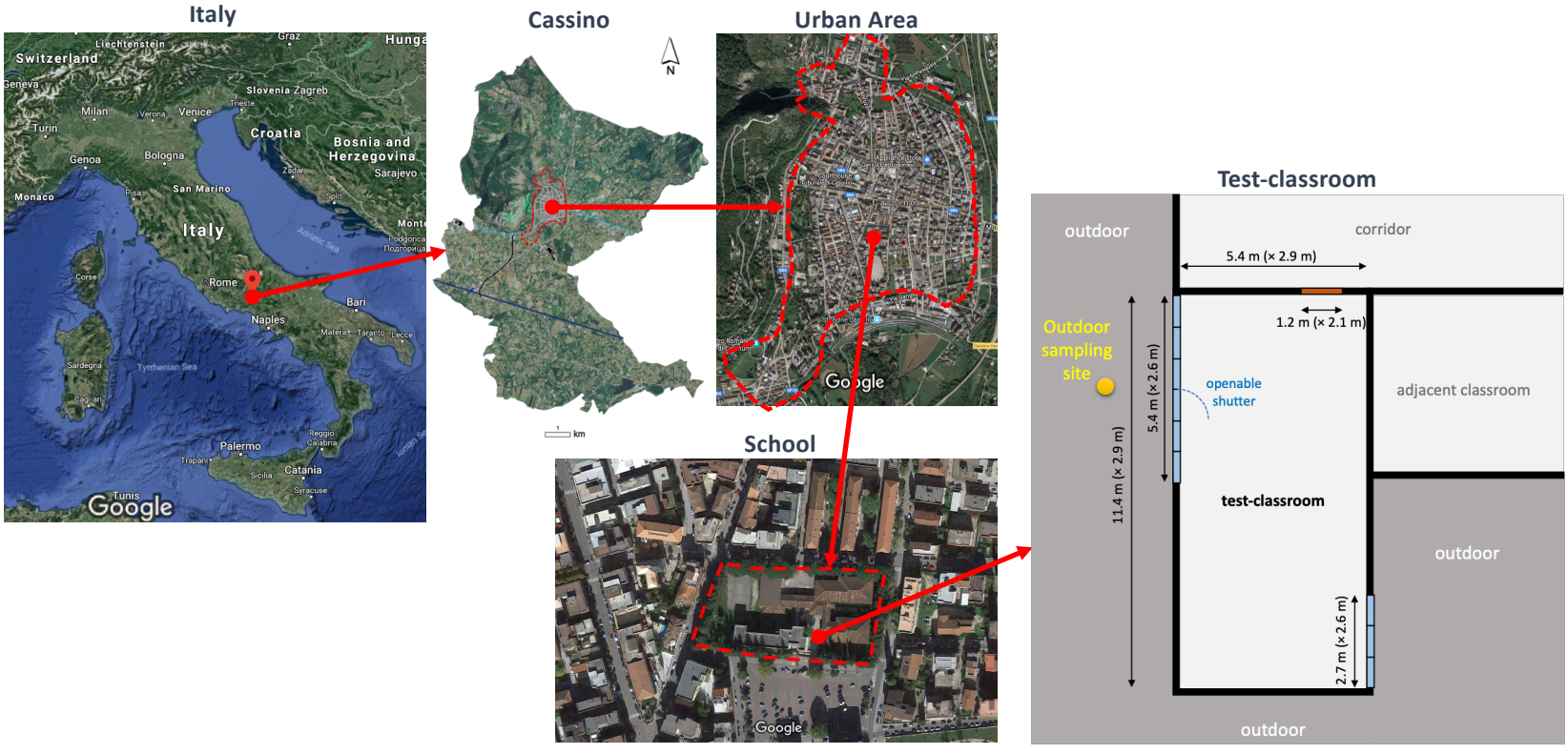

Italy
Switzerland
Liechtenstein
Slovenia
Zagreb
Milan
Venice
Turin
Croatia
Bosnia and Herzegovina
Genoa
Bologna
Monaco
San Marino
Italy
Rome
Bari
Naples
Sardegna
Tyrrhenian Sea
Palermo
Catania
Sicilia
Tunis
Google
Cassino
N
km
Urban Area
Google
School
Google
Test-classroom
outdoor
corridor
5.4 m (× 2.9 m)
1.2 m (× 2.1 m)
Outdoor sampling site
openable shutter
adjacent classroom
5.4 m (×2.6 m)
11.4 m (× 2.9 m)
test-classroom
outdoor
2.7 m (×2.6 m)
outdoor

Figure 2a

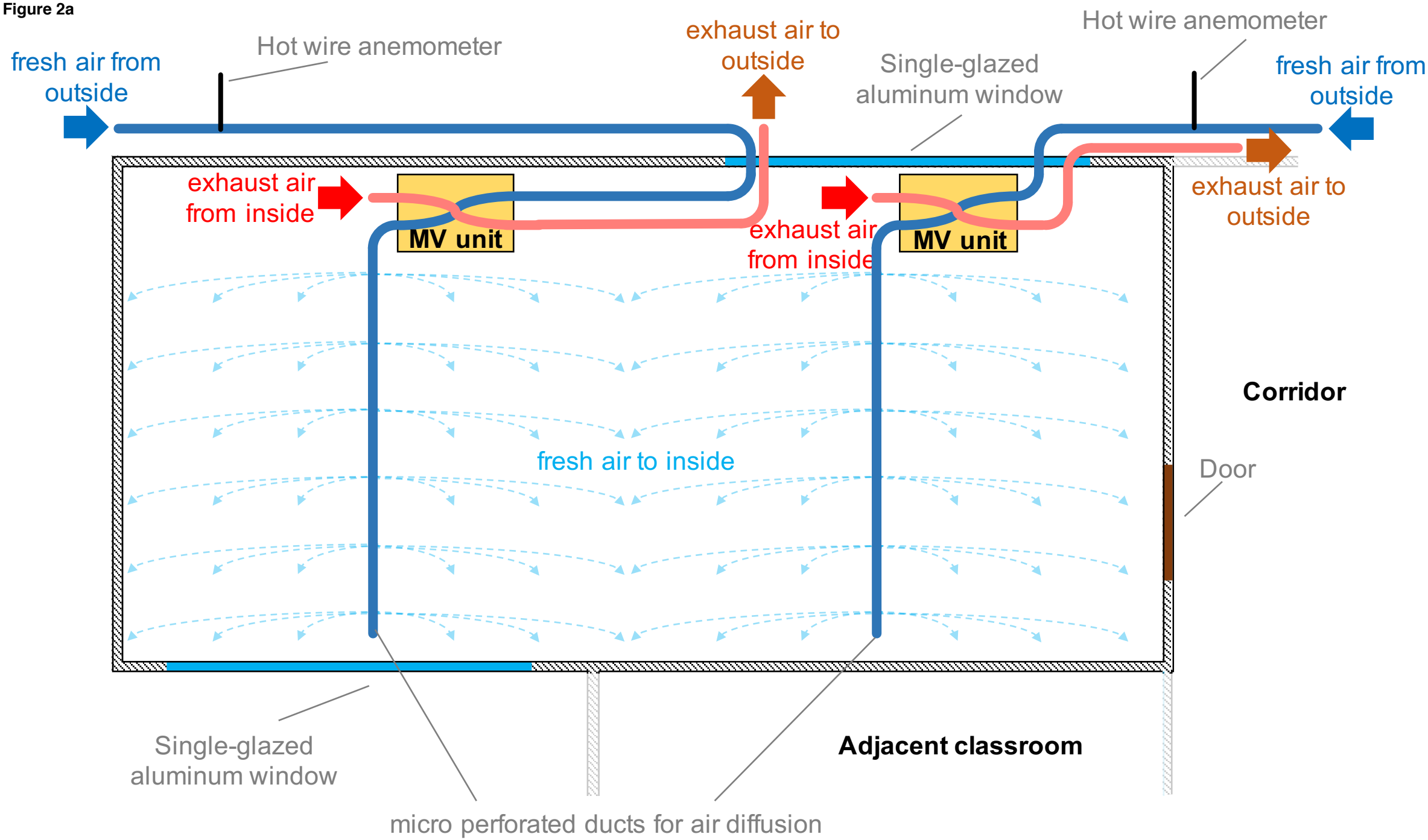

fresh air from outside
Hot wire anemometer
exhaust air to outside
Single-glazed aluminum window
Hot wire anemometer
fresh air from outside
exhaust air from inside
MV unit
exhaust air from inside
MV unit
exhaust air to outside
Corridor
fresh air to inside
Door
Single-glazed aluminum window
Adjacent classroom
micro perforated ducts for air diffusion

Figure 2b

Figure 3

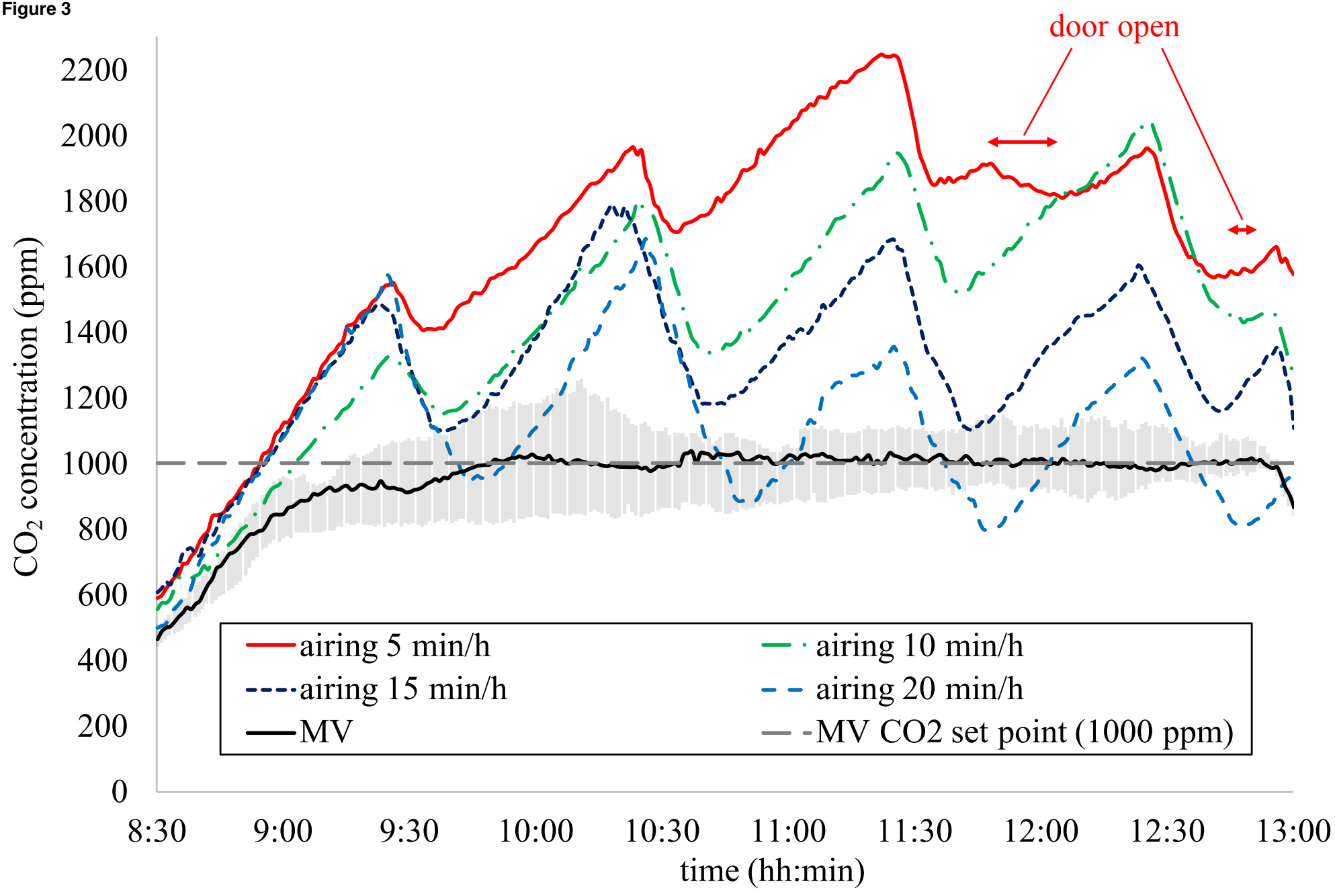

door open
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
CO_2 concentration (ppm)
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
time (hh:min)
airing 5 min/h
airing 10 min/h
airing 15 min/h
airing 20 min/h
MV
MV CO2 set point (1000 ppm)

Figure 4

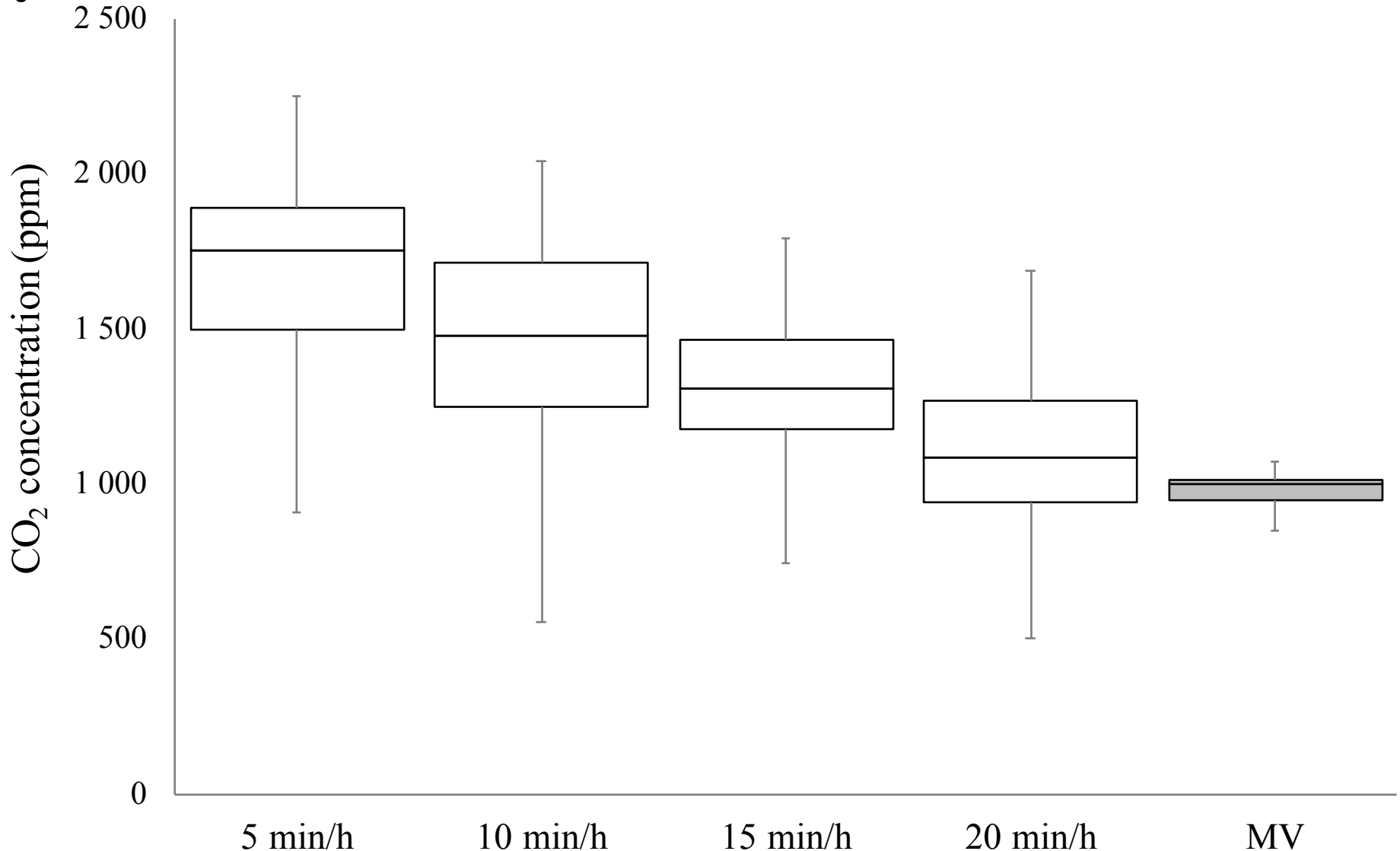

2 500
2 000
1 500
1 000
500
0
CO_2 concentration (ppm)
5 min/h
10 min/h
15 min/h
20 min/h
MV

Figure 5a

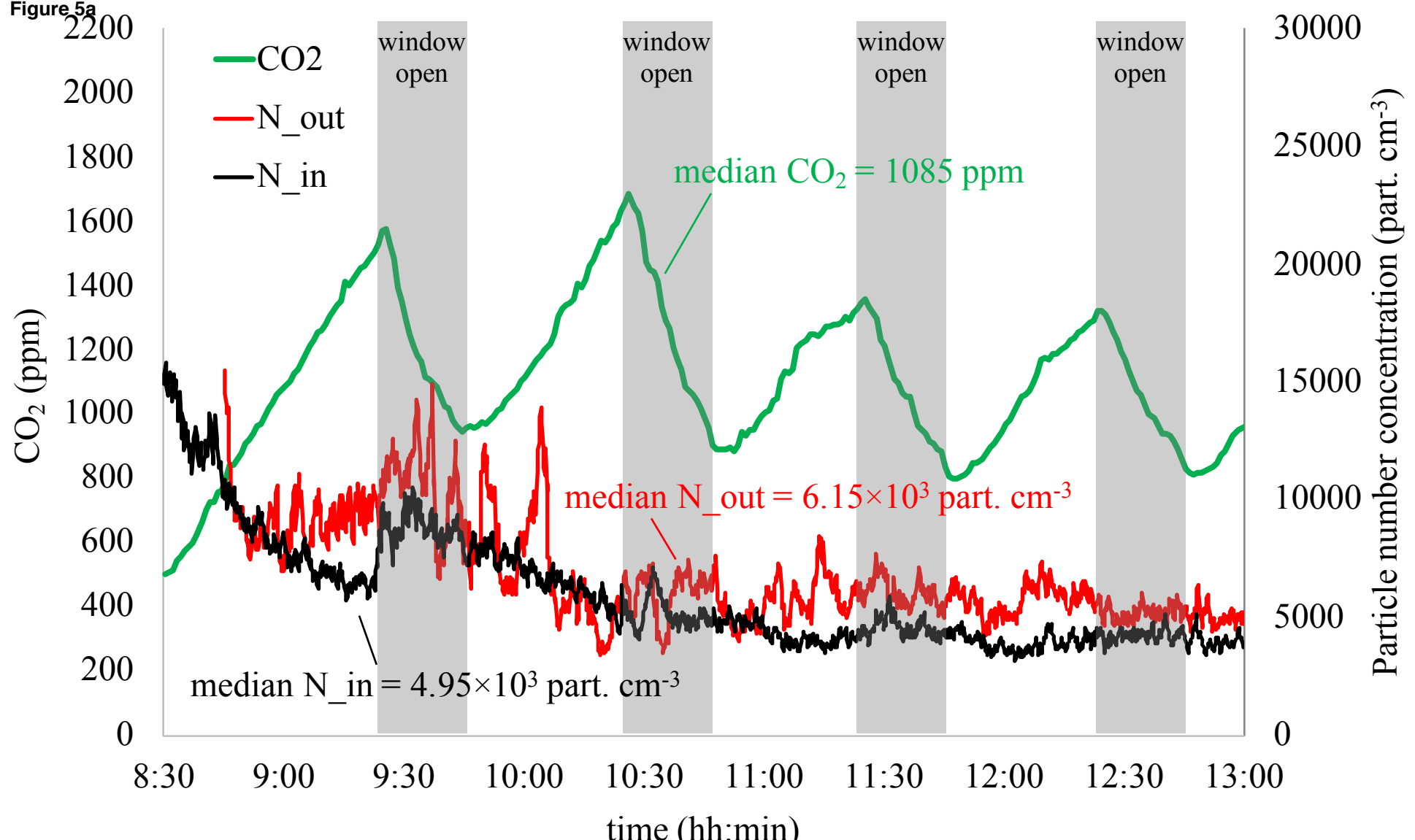

CO2
N_out
N_in
window open
window open
window open
window open
median CO_2 = 1085 ppm
median N_out = 6.15×10³ part. cm⁻³
median N_in = 4.95×10³ part. cm⁻³
CO_2 (ppm)
Particle number concentration (part. cm⁻³)
time (hh:min)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0
5000
10000
15000
20000
25000
30000
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00

Figure 5b

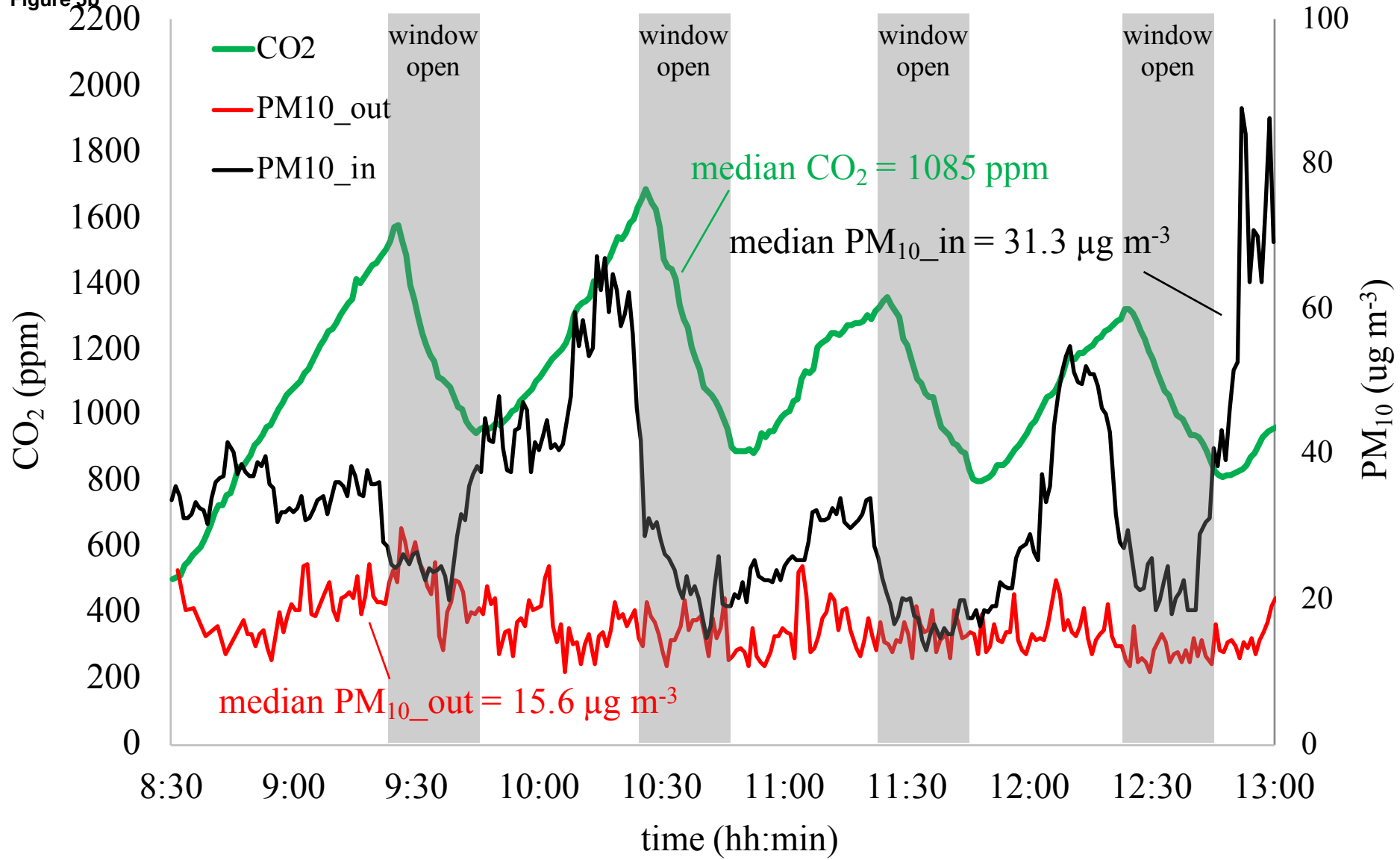

CO2
PM10_out
PM10_in
window open
window open
window open
window open
median CO_2 = 1085 ppm
median PM_{10}_in = 31.3 µg m^{-3}
median PM_{10}_out = 15.6 µg m^{-3}
CO_2 (ppm)
PM_{10} (ug m^{-3})
time (hh:min)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0
20
40
60
80
100
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00

Figure 6a

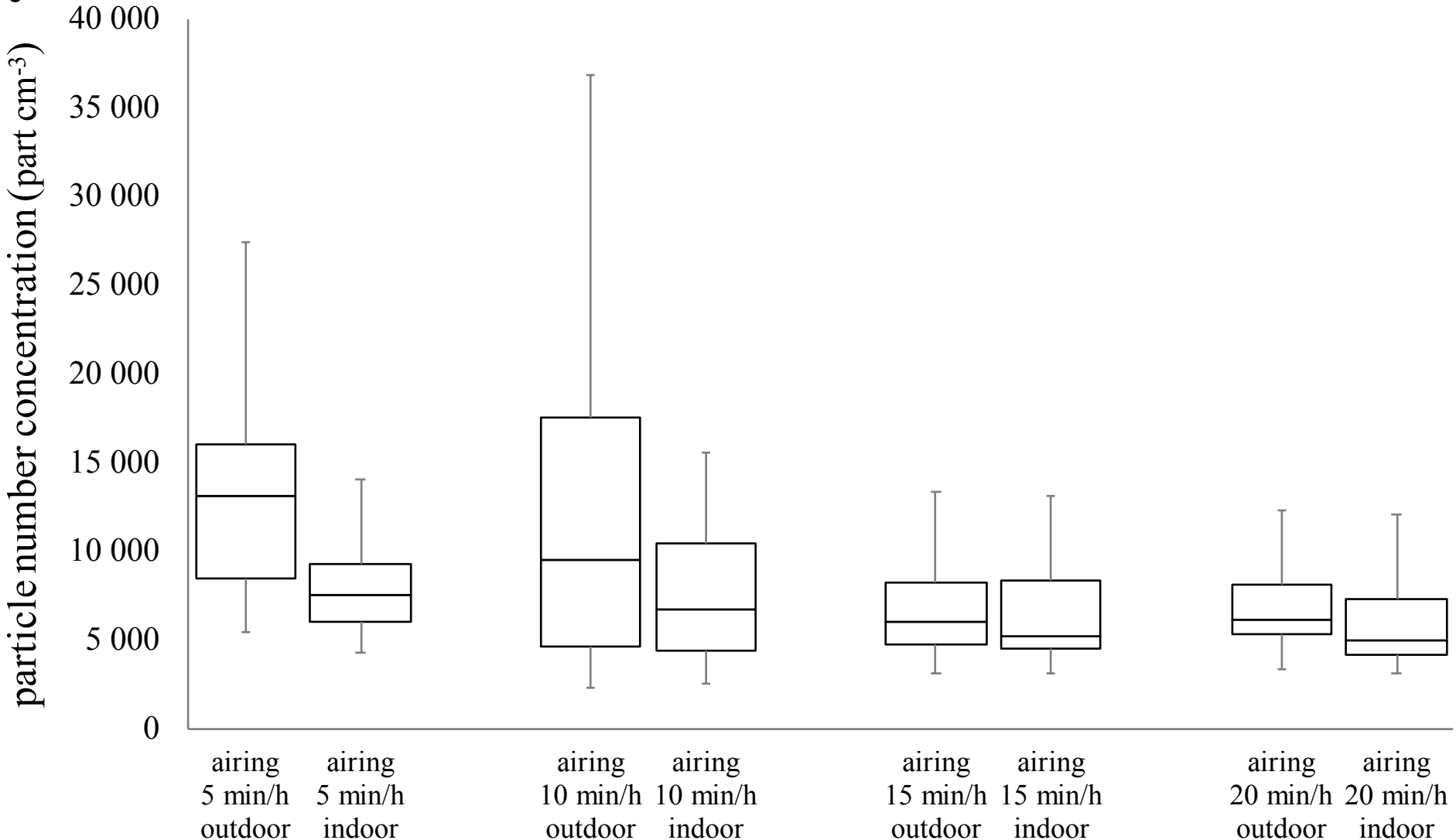

particle number concentration (part cm-3)
40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
airing 5 min/h outdoor
airing 5 min/h indoor
airing 10 min/h outdoor
airing 10 min/h indoor
airing 15 min/h outdoor
airing 15 min/h indoor
airing 20 min/h outdoor
airing 20 min/h indoor

Figure 6b

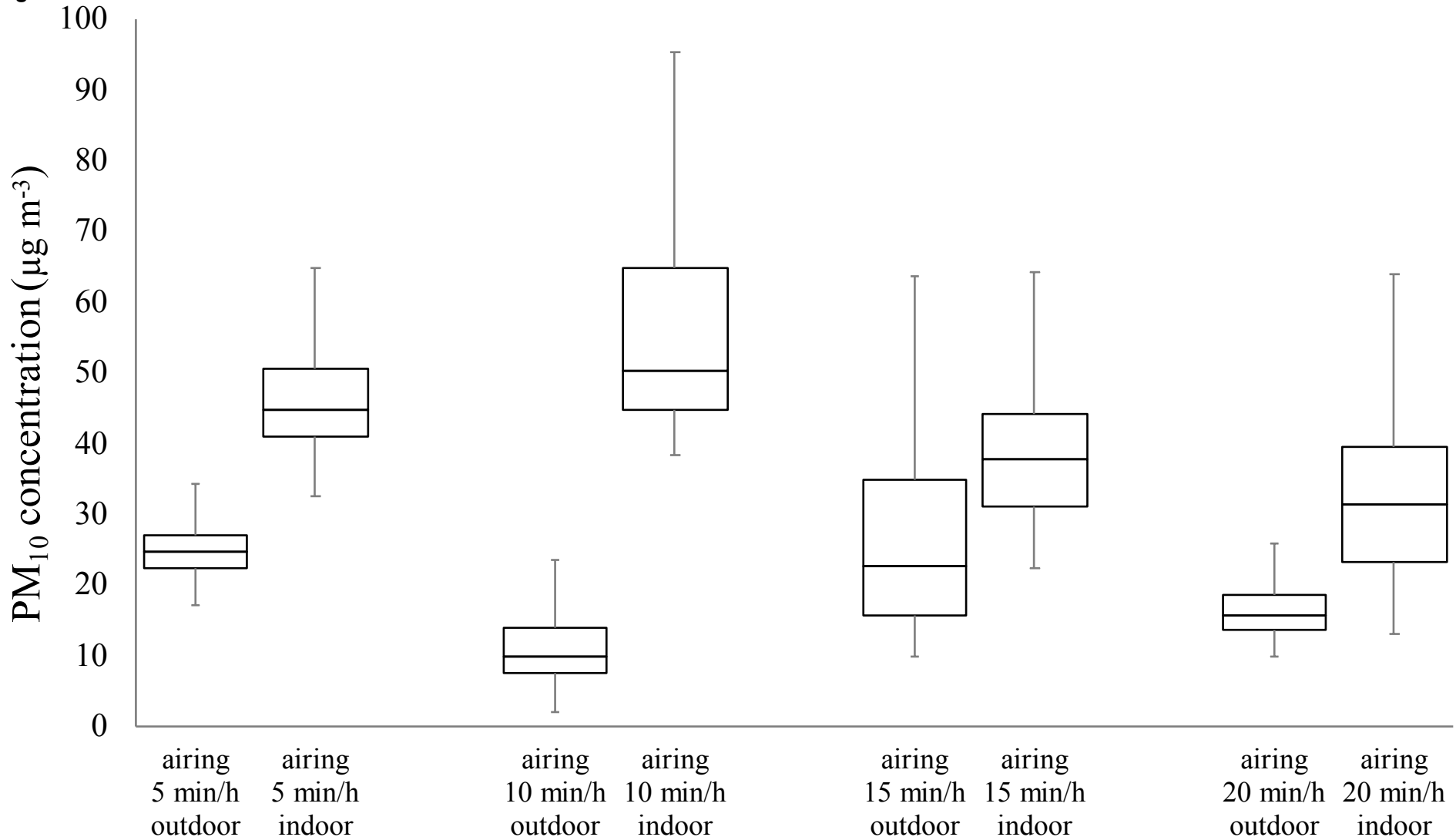

100
90
80
70
60
50
40
30
20
10
0
PM10 concentration (µg m-3)
airing 5 min/h outdoor
airing 5 min/h indoor
airing 10 min/h outdoor
airing 10 min/h indoor
airing 15 min/h outdoor
airing 15 min/h indoor
airing 20 min/h outdoor
airing 20 min/h indoor

Figure 7

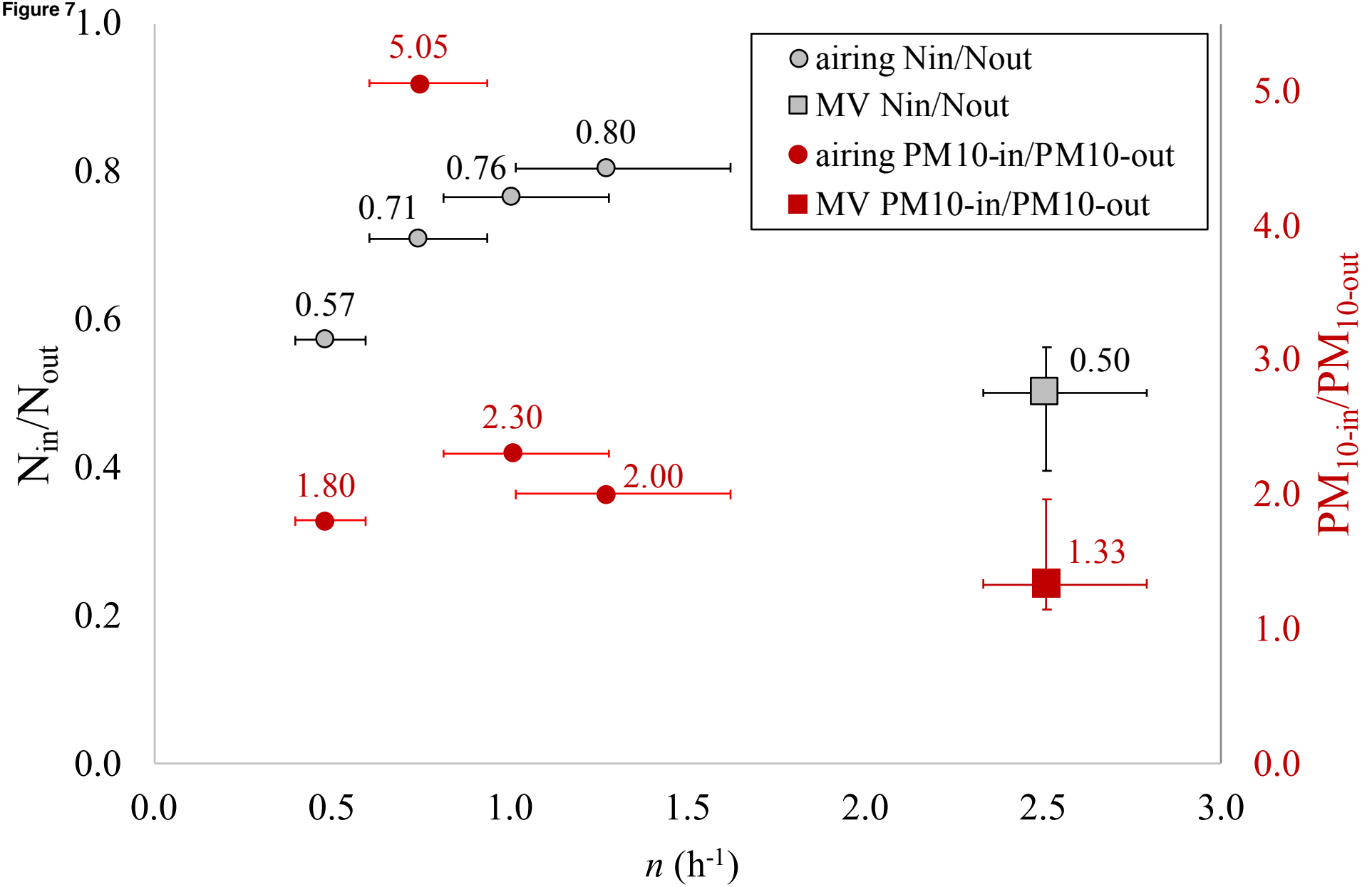

1.0
0.8
0.6
0.4
0.2
0.0
N_{in}/N_{out}
5.05
0.80
0.76
0.71
0.57
0.50
2.30
2.00
1.80
1.33
airing Nin/Nout
MV Nin/Nout
airing PM10-in/PM10-out
MV PM10-in/PM10-out
5.0
4.0
3.0
2.0
1.0
0.0
$PM_{10\text{-}in}/PM_{10\text{-}out}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
n (h^{-1})

Figure 8a

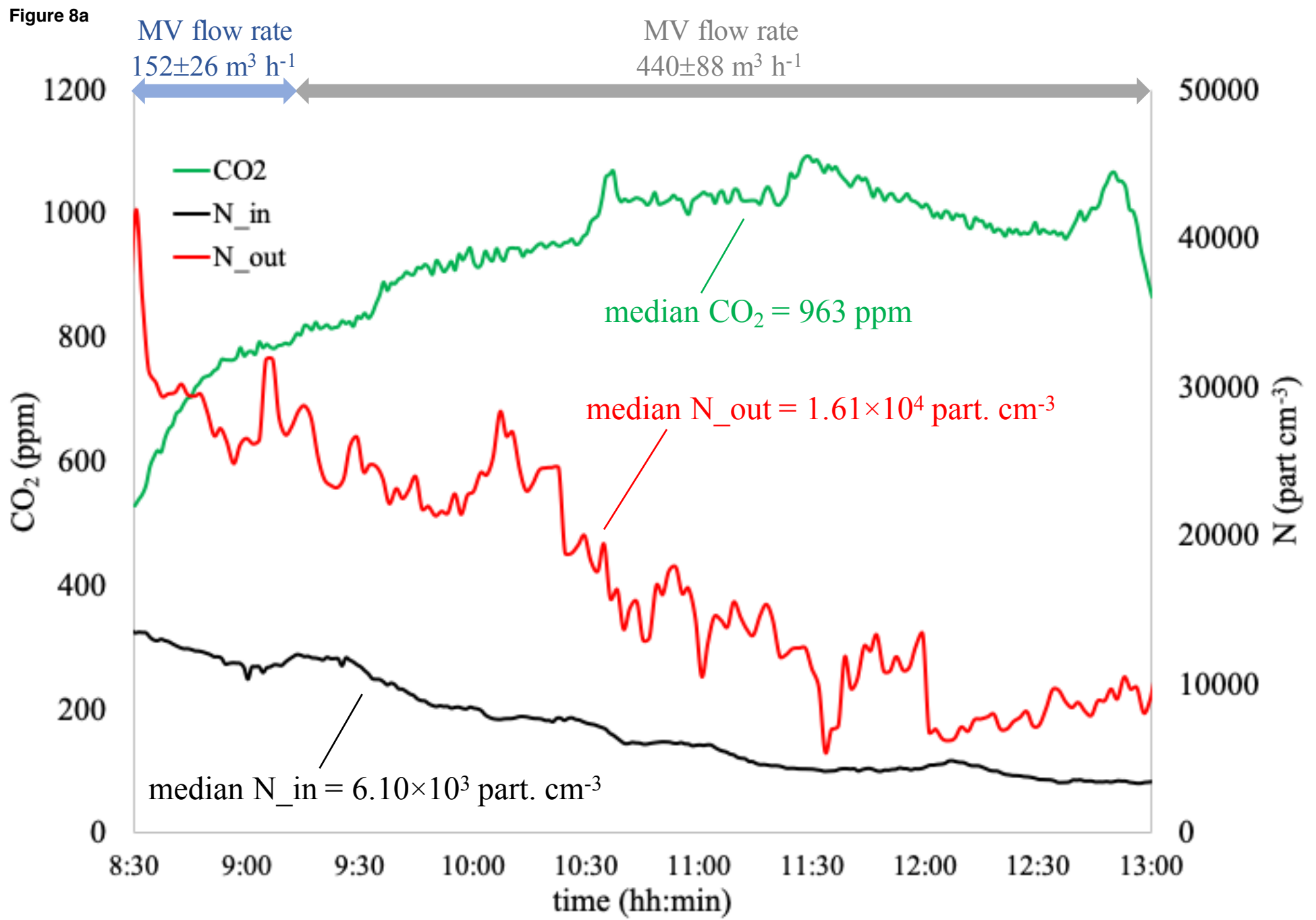
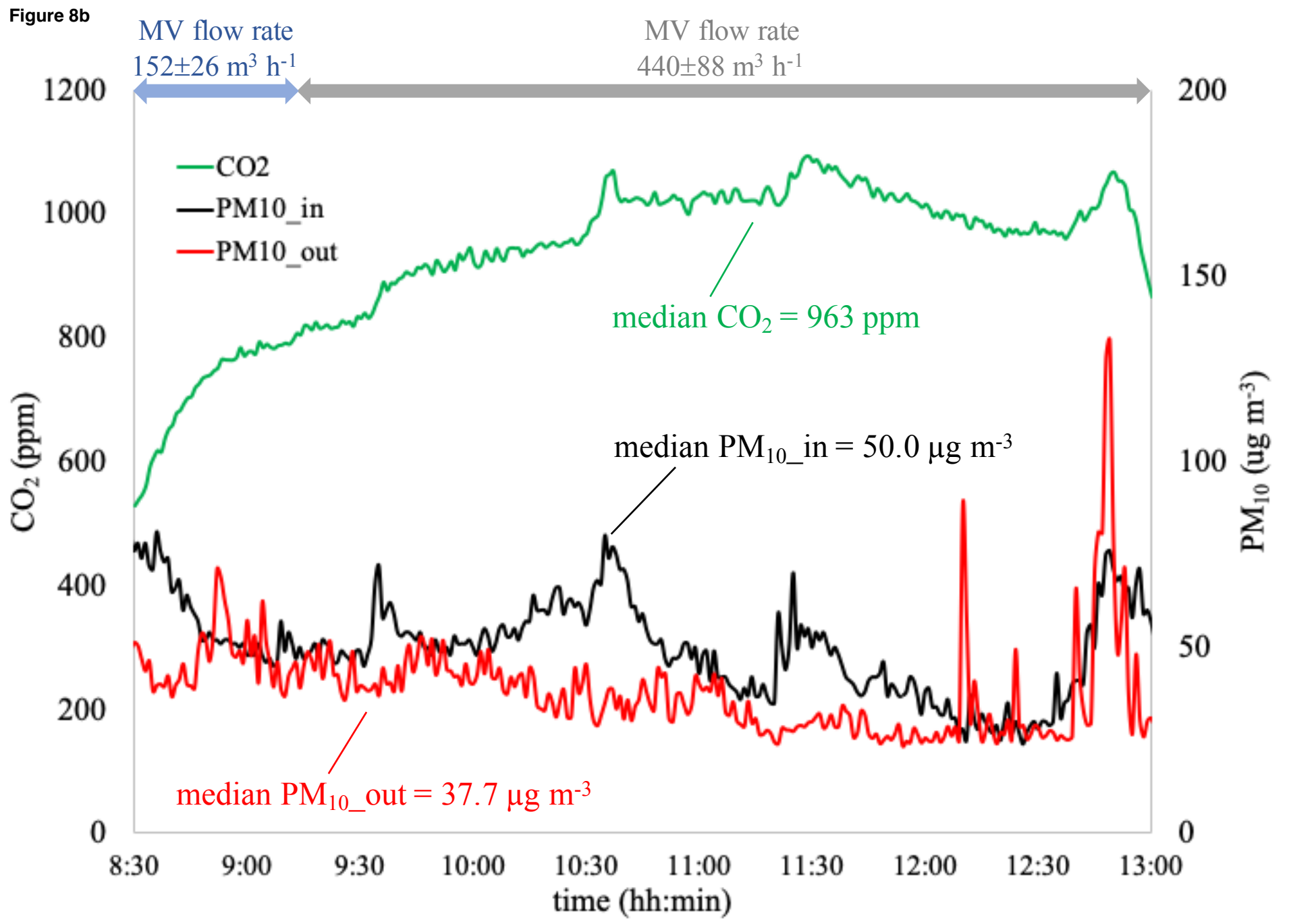

MV flow rate
152±26 m³ h⁻¹
MV flow rate
440±88 m³ h⁻¹
CO2
N_in
N_out
median CO₂ = 963 ppm
median N_out = 1.61×10⁴ part. cm⁻³
median N_in = 6.10×10³ part. cm⁻³
CO₂ (ppm)
N (part cm⁻³)
time (hh:min)
0
200
400
600
800
1000
1200
0
10000
20000
30000
40000
50000
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00

Figure 8b


MV flow rate
152±26 m³ h⁻¹
MV flow rate
440±88 m³ h⁻¹
CO2
PM10_in
PM10_out
median CO₂ = 963 ppm
median PM₁₀_in = 50.0 µg m⁻³
median PM₁₀_out = 37.7 µg m⁻³
CO₂ (ppm)
PM₁₀ (ug m⁻³)
time (hh:min)
1200
1000
800
600
400
200
0
200
150
100
50
0
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00