Particle Resuspension in School Gyms during Physical Activities

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ABSTRACT

The aim of this work was to quantify the exposure of children to particle resuspension in school gyms. In fact, although moderate standard aerobic activity is suggested for good health, adverse health effects could affect people exercising in micro-environments with ambient pollution. Overall, 12 micro-environments were chosen and analyzed in a 3-month experimental campaign. The different fractions of particulate matter (PM) were measured by means of photometers, calibrated for the specific aerosols studied through gravimetric samplers, whereas particle number distributions in the 0.5–20 μm range were continuously measured using an Aerodynamic Particle Sizer (APS) spectrometer. High PM concentration levels were measured in school gyms compared to outdoor values. The dominant source is the particle resuspension produced by the activity of exercising pupils and, among the various PM fractions, the effect on coarse particles ($PM_{10-2.5}$) was found to be the most important, with the related emissions factors measured in the range of 1.5–8.9 mg/min. During school activities, under natural ventilation conditions, the average coarse particle concentrations at the 12 school gyms investigated were found to be 4.8 ± 2.0 times higher than the background (outdoor) values. The key parameters are the number and intensity of the physical activities, which can be characterized by the total energy used by the students. Therefore, this study provides useful data on the exposure of students to airborne particles during periods of physical activity in gyms with natural ventilation.

Keywords: Particle resuspension; Coarse particles; Human activity; Indoor; Schools.

INTRODUCTION

Epidemiological and toxicological studies have shown strong links between particulate matter (PM) and adverse health effects, although there is a lack of agreement with regard to the particle properties, in terms of size, shape and chemical composition, that have the worst impact. Several studies have attempted to correlate the negative effects to particle mass concentration, PM_{10} or $PM_{2.5}$ (Loomis, 2000; Pope, 2000; Pope and Dockery, 2006), particle number concentration (ultrafine particles, UFPs, having a diameter less than 100 nm) (Hauser *et al.*, 2001) as well as surface area concentration (Giechaskiel *et al.*, 2009). As regards the health outcomes due to coarse particles ($PM_{10-2.5}$), epidemiological research has not found conclusive results. In fact, some studies showed no, or statistically insignificant, correlations (Schwartz *et al.*, 1999), whereas, more recently, Brunekreef and Forsberg (2005), Alexis *et al.* (2006), and Yeatts *et al.* (2007) found links between coarse particles

and asthma, chronic obstructive pulmonary disease, and heart rate variability. With regard to short term effects, coarse particles have an equal or higher influence than fine particles, suggesting that coarse PM may lead to adverse responses in the lung that trigger processes leading to hospital admissions (Brunekreef and Forsberg, 2005). Therefore, special consideration should be given to the study and regulation of coarse particles in particular, separate from efforts focused on fine particles.

Children have the greatest susceptibility when exposed to polluted air, mainly because of their higher metabolic rates and greater levels of physical activity, which cause an increase in minute ventilation (i.e., the volume of air inhaled, or exhaled, from a person's lungs in a minute). Furthermore the developing lungs of children are especially vulnerable to the negative consequences of particle inhalation (Gauderman *et al.*, 2004; Schwartz, 2004).

Schools are considered micro-environments characterized by high PM concentrations, especially when the buildings are located near highly trafficked roads (Fromme *et al.*, 2007; Diapouli *et al.*, 2008; Buonanno *et al.*, 2011a; Canha *et al.*, 2011). PM_{10} concentrations in schools are higher than outdoor ones due to dust resuspension caused by the activity of the students (Brunekreef *et al.*, 1997; Fromme *et al.*, 2008). Here, resuspension is the process by which

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particles are reintroduced into the air from a surface on which they were previously deposited. Although the first scientific studies of resuspension processes focused on soil erosion and the related transport of dust, recent studies have found that particle resuspension in indoor micro-environments could be an important factor in indoor air quality evaluation (Kim *et al.*, 2010). Indeed, this process is strongly related to the transmission of human diseases and the dispersion of allergens (Thatcher and Layton, 1995; Hu *et al.*, 2005). Moreover, the total amount of particulate matter deposited in the respiratory tract during moderate exercise may be up to five times higher than at the rest, increasing along with the intensity of physical activity (Daigle *et al.*, 2003). Moreover, Braniš *et al.* (2009, 2011a, b) found high concentrations of coarse PM in an urban school gyms, and showed that concentrations increased along with the activity levels of exercising students due to resuspension, whereas the effect of the outdoor air on $PM_{10-2.5}$ fraction was negligible. Their experiment was carried out in a central part of Prague (Czech Republic), sampling air through a five-stage cascade impactor in order to obtain 24-h average concentrations. Fromme *et al.* (2008) also noted that the physical activity of pupils leads to the resuspension of indoor coarse particles, and is the main reason for rises in the level of PM_{10} in classrooms. This relationship was also highlighted by Goyal and Khare (2009), who carried out a study on indoor-outdoor PM concentrations by monitoring a classroom in a naturally ventilated school building located near an urban roadway in Delhi City (India). The results showed that half-hourly average indoor PM_{10} concentrations were highest when the students were most active in the room.

The aim of the current study was to investigate the physical properties of aerosols in 12 naturally ventilated school gyms while students were exercising, in order to obtain data for exposure analysis. During the experimental tests, different PM fraction concentrations, particle number distributions and CO_2 concentrations were measured using two DustTrak™ DRX Aerosol Monitors, an Aerodynamic Particle Sizer (APS) spectrometer, and a non-dispersive infrared (NDIR) sensor, respectively. These instruments make it possible to directly correlate the $PM_{10-2.5}$ fraction to the number of students and their metabolic rates, as they carry out continuous measurements (1 Hz frequency).

EXPERIMENTAL METHOD

The Sampling Sites

Tests were carried out from March to May 2011 in 12 school gyms (G1–G12) in Cassino, Central Italy (41°30'0"N–13°50'0"E), which can be considered a typical, busy mid-sized Italian town (resident population: 33,000 inhabitants; daily commuter workers and students: 20,000; surface area: 83 m²). A good mix of school gyms, in terms of location (near and far from major streets), dimension (low, medium and large volume), number of exercising pupils, and building materials were chosen, in order to analyze different exposure situations. All the schools use natural ventilation systems, and their main characteristics are reported in Table 1. The

school gyms are generally cleaned twice a week. The total volume of the school gyms ranges from 585 to 9650 m³, with the minimum and maximum values corresponding to G4 and G1, respectively. With the exception of G4 (marble) and G7 (resin), all the school gyms have a linoleum or rubber floor, whereas all the gym walls are plastered. Useful information on the number of windows and doors, as well as the number of pupils exercising during the day (ranging from 22 in the gym G4 to 179 in G2), along with the corresponding gym activities, are also reported in Table 1.

Instrumentation

The measurement of the different PM fractions (PM_{10}, $PM_{2.5}$, and PM_1) using obtained by two DustTrak™ DRX Aerosol Monitors (Model 8534, TSI Incorporated, St. Paul, MN, USA). It should be noted that the DustTrak operates on the basis of a light scattering technique, where the amount of scattered light is proportional to the aerosol particle volume concentration. The PM measurement data obtained through this device were corrected on the basis of the calibration through the gravimetric time-integrated technique, which represents the reference method in air quality standard measurements. In particular, the DustTrak was calibrated at the beginning of each experimental campaign (for the specific aerosol studied) using a gravimetric time-integrated sampler (Zambelli 6000 Plus). Additionally, both units were calibrated daily to a zero filter, used to re-zero the units and ensure reading accuracy. The gravimetric technique is based on the measurement of the gas flow rate through a low porosity filter and the subsequent measurement of PM_{10} mass. The dimensional and metrological characteristics of the impactors for PM_{10} sampling are described in EN 12341:2001. The gravimetric sampler is periodically calibrated in order to guarantee the metrological traceability to SI (Buonanno *et al.*, 2010). The particulate levels were measured concurrently by each DustTrak and the gravimetric sampler. These instruments were placed at the same locations (one in the school gym and the other in the outdoor) and at similar sampling heights over a 6-h sampling period. The correlation curves were plotted and the correlation coefficient between each DustTrak and the gravimetric measurement was between 0.92 and 0.98, for PM_{10} and $PM_{2.5}$, respectively.

The indoor CO_2 concentration was determined on the basis of a non-dispersive infrared (NDIR) sensor, the TSI Model 7515 IAQ-CALC™, calibrated by the manufacturer at the beginning of the experimental campaign. In order to correct for the outdoor contribution of carbon dioxide, ambient concentrations, obtained from Italian Environmental Protection Agency monitoring stations, were subtracted from the indoor ones.

Particle number distribution measurements were obtained using a TSI Model 3321 Aerodynamic Particle Sizer (APS) spectrometer which is able to measure particle size distribution and number concentration in real time, in the range from 0.5 to 20 μm. The measurement is based on the time of flight (*TOF*) calculation (average velocity across the timing gate) of the particle at the exit of an accelerating nozzle. This method consists of drawing the aerosol into the inlet and immediately splitting it into a sample flow (1

Table 1. Characteristics of the school gyms investigated.

Gym	Volume (m^3)/ Floor area (m^2)	Wall material (floor)	Notes	Exercising Students	Activities carried out by the students
G1	9650/1000	Beton (Linoleum)	Windows closed; Two emergency doors opened late in the morning.	73	Running, gymnastics, leaping, jumping, volleyball.
G2	2910/320	Plaster (Linoleum)	One door opened; Emergency door opened late in the morning.	179	Running, gymnastics, aerobics, leaping, jumping, playing ball.
G3	2925/325	Plaster (Rubber)	Three windows opened.	101	Running, gymnastics, jumping with a cord, volleyball.
G4	585/146	Plaster (Marble)	Four windows opened; Doors opened.	22	Running, gymnastics, basketball, volleyball.
G5	4233/560	Plaster (Linoleum)	One door always opened; Emergency door randomly opened.	136	Running, gymnastics, volleyball, jumping with and without a cord, football.
G6	3861/540	Brick (Linoleum)	One door opened; Emergency door randomly opened.	67	Running, gymnastics, volleyball, jumping with a cord.
G7	3024/400	Plaster (Resin)	Doors and windows closed.	82	Running, gymnastics, basketball, jumping with a cord.
G8	4104/684	Plaster (Linoleum)	One door opened; Emergency door randomly opened.	95	Running, gymnastics, hit-ball.
G9	2700/450	Plaster and wall plastic paper (Rubber)	One door opened; Emergency door opened late in the morning.	84	Running, gymnastics, volleyball, football.
G10	1966/312	Plaster (Linoleum)	Emergency door opened late in the morning.	111	Running, gymnastics, football, playing ball.
G11	4446/684	Plaster (Linoleum)	Emergency door opened.	65	Running, gymnastics, hit-ball, volleyball.
G12	2250/375	Plaster (Rubber)	One door opened; Emergency door opened late in the morning,	60	Running, gymnastics, volleyball.

L/min), through an inner nozzle, and a sheath flow (4 L/min), through an outer nozzle. The filtered sheath flow is then reunited with the sample flow at the accelerating orifice nozzle. This flow confines the sample particles to the center stream and accelerates the air flow around them. Particle inertia causes the particle velocity to lag behind the velocity of the entraining gas. In this way it manages to measure particle velocity in the optics chamber, which also provides particle aerodynamic sizing.

Methodology Description

A DustTrak, the APS spectrometer and the IAQ-CALC, used to measure PM concentrations, number distributions and CO_2 concentrations inside the school gyms, respectively, were generally placed in the center of the gyms (at a minimum distance of 1 m from the walls), at a height of about 1.5 m from the ground and close enough the exercising pupils in order to consider as negligible the spatial variations of concentrations. Furthermore, both minimal inconvenience to the children and the researchers' safety were considered in the experimental design. Each school was monitored for one school day, and measurements started 5–10 min before the beginning of the activities in the gyms. The monitoring

activities typically started at 8.30 a.m. and ended at 1.30 p.m. A second DustTrak was placed outside the school (at a distance of about 10 m from the buildings and at a height of about 1.5 m from the ground) in order to monitor the ambient PM concentrations. Measurement data from the DustTraks, APS spectrometer and IAQ-CALC were obtained with a 30-s time resolution.

During the tests, the only indoor source was the dust resuspension due to the pupils' movements, and thus their activity in the gym was carefully monitored by the researchers in a written form. In particular, for each test, the exact number of exercising students, the type of activity and the corresponding time were recorded. Such details allowed the development of indicators in order to precisely correlate the students' activities to the coarse particle concentrations.

The emission of coarse particles ($PM_{10-2.5}$) was characterized using the mass balance equation proposed by Chen *et al.* (2000) and Thatcher and Layton (1995):

$$\frac{dC_{in}}{dt} = P \cdot AER \cdot C_{out} + \frac{Q_s}{V} + (AER + k) \cdot C_{in} \qquad (1)$$

This formula was used to determine the indoor particle concentration levels taking into account the contributions from indoor and outdoor sources, the deposition rate of particles on indoor surfaces, and the air exchange ratio. In particular, C_{in} and C_{out} stand for indoor and outdoor particle concentrations, respectively, P is the penetration efficiency, k is the deposition rate, Q_s is the indoor particle generation rate, t is time and V is the efficient volume of the plenum. Eq. (1) can be simplified using average values instead of functions, and also making further assumptions about the experimental conditions, as reported in He *et al.* (2004) (e.g., P is assumed close to one; when no indoor source is in operation, the indoor particle concentration can be approximated by the outdoor particle concentration, and the initial indoor particle concentration could be used to replace the outdoor one). We thus evaluated the emission factor ($EF_{PM_{10-2.5}}$) (both total and per pupil) referring to the coarse fraction by using the simplified equation proposed by He *et al.* (2004) for indoor sources:

$$EF_{PM_{10-2.5}} = V \cdot \left[\frac{C_{in} - C_{in,0}}{\Delta t} + \left(\overline{AER+k} \right) \cdot \overline{C_{in}} - AER \cdot C_{in,0} \right]$$

(2)

where C_{in} and $C_{in,0}$ represent the peak and initial indoor concentrations (in terms of $PM_{10-2.5}$), respectively, $\overline{AER+k}$ is the average total removal rate (taking into account the deposition rate, k, and the air exchange rate, AER), ΔT is the time difference between the initial and peak concentration, and V is the efficient volume of the gyms. This equation ignores the effects of particle dynamics, such as condensation, evaporation and coagulation, since these are considered to be minor, particularly under the conditions normally encountered in indoor environments (Thatcher and Layton, 1995).

RESULTS AND DISCUSSION

PM Fraction Concentrations in the School Gyms Analyzed

Table 2 reports the maximum and hourly mean PM fraction concentrations monitored inside the school gyms during the activities, along with the corresponding background values.

With regard to the indoor mean PM concentrations, the following ranges were found: 17–95 μg/m³ for $PM_{2.5}$ and 33–204 μg/m³ for PM_{10}, showing great variation amongst the gyms. With the exception of school gym G1, in all the analyzed cases the PM_{10} mean values exceed the daily threshold value (50 μg/m³) for urban areas (EU, 1999): the corresponding maximum values are generally much higher than 100 μg/m³. These differences can be mainly ascribed to the activities being carried out and the number of pupils, as explained in later in this work. In fact, the outdoor PM fractions show have mean values that are always lower than the corresponding indoor ones, highlighting the presence of an indoor source (i.e., resuspension) due to the activity of pupils.

In addition, the $PM_{2.5}/PM_{10}$ outdoor ratios are always higher than the indoor ones, showing that indoor particle generation due to resuspension mostly lead to an increase in the coarse particle fraction compared to the fine one. In order to quantify the strength of the resuspension, Fig. 1(a) shows the minimum and maximum values, 1st and 3rd quartile and median values of the increases in fine, coarse and PM_{10} fractions, with respect to the outdoor values for each school gym.

The mean increase in indoor PM_{10} for all the examined school gyms with regard to the outdoor PM_{10} is 59 μg/m³, and this is due to the coarse fraction, which contributes about 66% of the total. In fact, the $PM_{10-2.5}$ fraction has a median value greater than 30 μg/m³, with exception of G1 and G8, and thus the activities in school gyms have to be considered an important source of the coarse fraction. During these activities, under natural ventilation conditions, the average coarse particle concentrations in the 12 school gyms investigated are 4.8 ± 2.0 times higher than corresponding outdoor concentrations, with the maximum values found for school gym G6 (Fig. 1(b)).

The volume of the gyms has no significant effect on the results, and while an exponential decay of PM_{10} is observed as the volume increases, there is a low coefficient of

Table 2. Maximum and hourly mean outdoor and indoor PM fractions, air exchange rates and coarse PM emission factors.

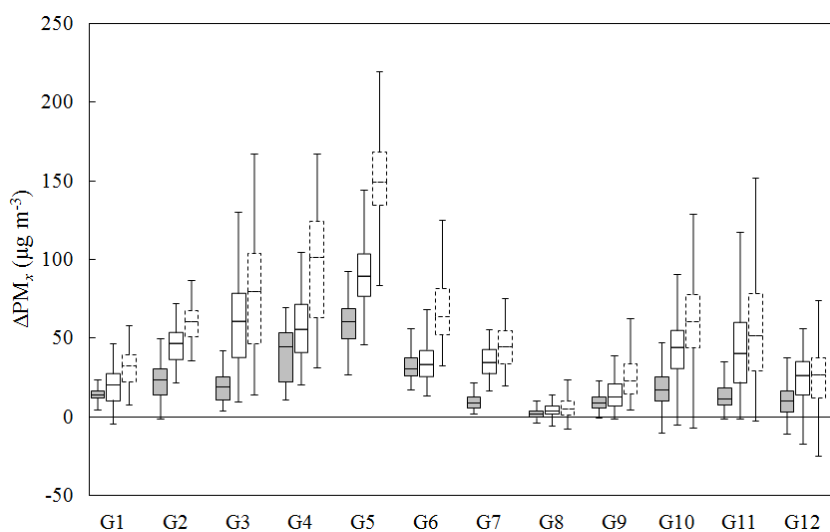| School gyms	Mean (and max) indoor PM_{10} (μg/m³)	Mean (and max) indoor $PM_{2.5}$ (μg/m³)	Mean outdoor PM_{10} (μg/m³)	Mean outdoor $PM_{2.5}$ (μg/m³)	$PM_{2.5}/PM_{10}$ indoor	$PM_{2.5}/PM_{10}$ outdoor	Air exchange rate (AER) (L/s/pupil)/(h⁻¹)	$EF_{PM_{10-2.5}}$ (mg/min)/ (μg/min/pupil)
G1	33 (51)	17 (27)	5.4	3.1	0.51	0.57	3.9/0.11	4.9/68
G2	149 (214)	84 (110)	70	60	0.56	0.86	3.8/0.84	3.7/21
G3	104 (191)	31 (54)	24	12	0.30	0.50	3.5/0.44	7.5/74
G4	162 (228)	92 (117)	61	47	0.57	0.77	1.0/0.14	1.5/66
G5	204 (280)	95 (127)	54	34	0.47	0.63	3.8/0.44	8.9/65
G6	77 (172)	41 (111)	13	10	0.53	0.77	3.5/0.22	5.2/78
G7	70 (101)	27 (40)	25	18	0.39	0.72	5.2/0.51	3.3/41
G8	52 (71)	24 (35)	47	23	0.46	0.49	2.1/0.18	6.5/69
G9	83 (135)	60 (102)	60	51	0.72	0.85	3.4/0.38	2.2/26
G10	133 (208)	55 (85)	72	38	0.41	0.53	6.1/1.24	2.0/18
G11	81 (287)	26 (79)	29	14	0.32	0.48	3.4/0.18	4.5/69
G12	79 (126)	31 (60)	52	31	0.39	0.60	5.3/0.51	5.8/97

Fig. 1(a). Fine (grey boxplot), coarse (continuous line boxplot) and PM_{10} (dashed boxplot) increments in respect to the corresponding outdoor concentrations for the school gyms analyzed.
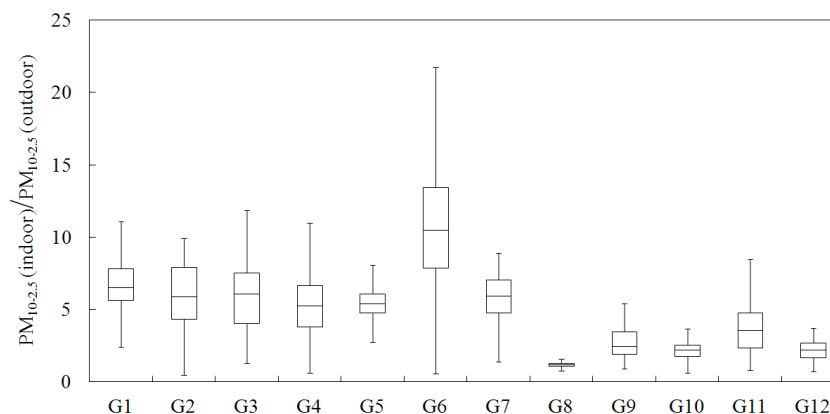

Fig. 1(b). Indoor/Outdoor coarse fraction ratio for the school gyms analyzed.

determination (R^2 = 0.46). The correlations with $PM_{2.5}$ and $PM_{10–2.5}$ are even weaker.

Table 2 shows the Air Exchange Rates (AERs) per pupil for each school determined on the basis of the CO_2 decay rates. A median value of 3.6 L/s/pupil (with a 1st and 3rd quartile of 3.4 and 4.2 L/s/pupil, respectively) is found for all the schools. With regard to gym size, the average AER was measured equal to 0.42 h^{-1} (with 1st and 3rd quartiles of 0.17 and 0.51 h^{-1}, respectively). Such AER values are typical of naturally-ventilated school buildings, as seen in the results of other studies (e.g., Kõiv, 2007; Weichenthal *et al.*, 2008).

Particle Size Mass Distribution Trends in the School Gyms

In order to better reveal the correlation between the exercising pupils and coarse particle concentrations, Fig. 2 reports the particle mass distributions as a function of time for the school gyms with the highest number of exercising pupils (G2, G3, G5, and G10). The mass distribution was evaluated from the number particle distribution obtained from the APS 3321 by applying a particle density value of 1.7 g/cm^3. This particle density was chosen by comparing

the $PM_{10–2.5}$ concentration evaluated from the APS 3321 distribution to the one measured through the calibrated DustTrak.

The concentration of each particle diameter as a function of the time makes it possible to correlate indoor resuspension to the activities in the gym, as monitored by the researchers. Fig. 2(a) shows the particle mass distribution evolution measured at the G2 gym (primary school, 6-to10-year old students). Peak events correspond to the presence of about 40 students per hour doing exercises like running, jumping (with and without a rope) and playing ball. The particle mass distribution mode diameter during these activities was in the range 5–7 µm.

The results for a secondary school (G3, 11- to 13-year old students) are reported in Fig. 2(b). A peak is shown around 9.45 a.m., followed by a quite constant distribution. The peak can be related to the activity of about 30 students running in the school gym, and the main gym activities during the rest of the day were jumping, volleyball and running in place. The mode diameter varies from 3 µm, during the highest concentration, to 6 µm, during the rest of the activity period.

In the G5 case, as shown in Fig. 2(c), a peak event is clearly visible at about 9.30 a.m., when more than 40 students (high school, 14–18 years old) were simultaneously running and jumping with ropes. The number of the students then fell to less than 20. A higher mode in the particle mass distribution (> 8 μm) was found in this school gym.

Finally, Fig. 2(d) shows the results for a primary school (G10) with a mean of about 30 students per hour, whose their main activities were gymnastics exercises and dancing. The mode diameter is practically constant, and equal to about 6 μm.

The results presented above reveal a strong correlation between particle resuspension and both number of students and type of activities they engaged in, and this will be discussed in more detail below.

The high increase in the coarse particle fraction during the students' physical activities leads to a greater amount of inhaled $PM_{10-2.5}$ fraction being deposited in the respiratory system. To illustrate this, we evaluated the total deposition (deposition within the entire respiratory tract) of inhaled coarse ($PM_{10-2.5}$) mass fractions during one hour (10.30–11.30) of physical activities performed by 10-year old students in the G2 gym. Furthermore, we extended our analysis to the super-micrometer ($PM_{10-1.0}$) mass fraction in order to highlight the relevant increase in the coarse fraction ($PM_{10-2.5}$) with respect to the total super-micrometer mass fraction. Morawska *et al.* (2008) identified a clear and distinct separation between the location of the modes for a substantial number of environments worldwide and particle metrics. The coarse mode provides information mainly on the particles generated by mechanical processes, but the contribution from combustion process modes (nucleation and accumulation modes) becomes significant for some environments. Submicrometer particle measurements (nucleation and accumulation modes) provide very good information about contributions from combustion processes, and enable a much better distinctions to be made between combustion and mechanically generated aerosols (Morawska
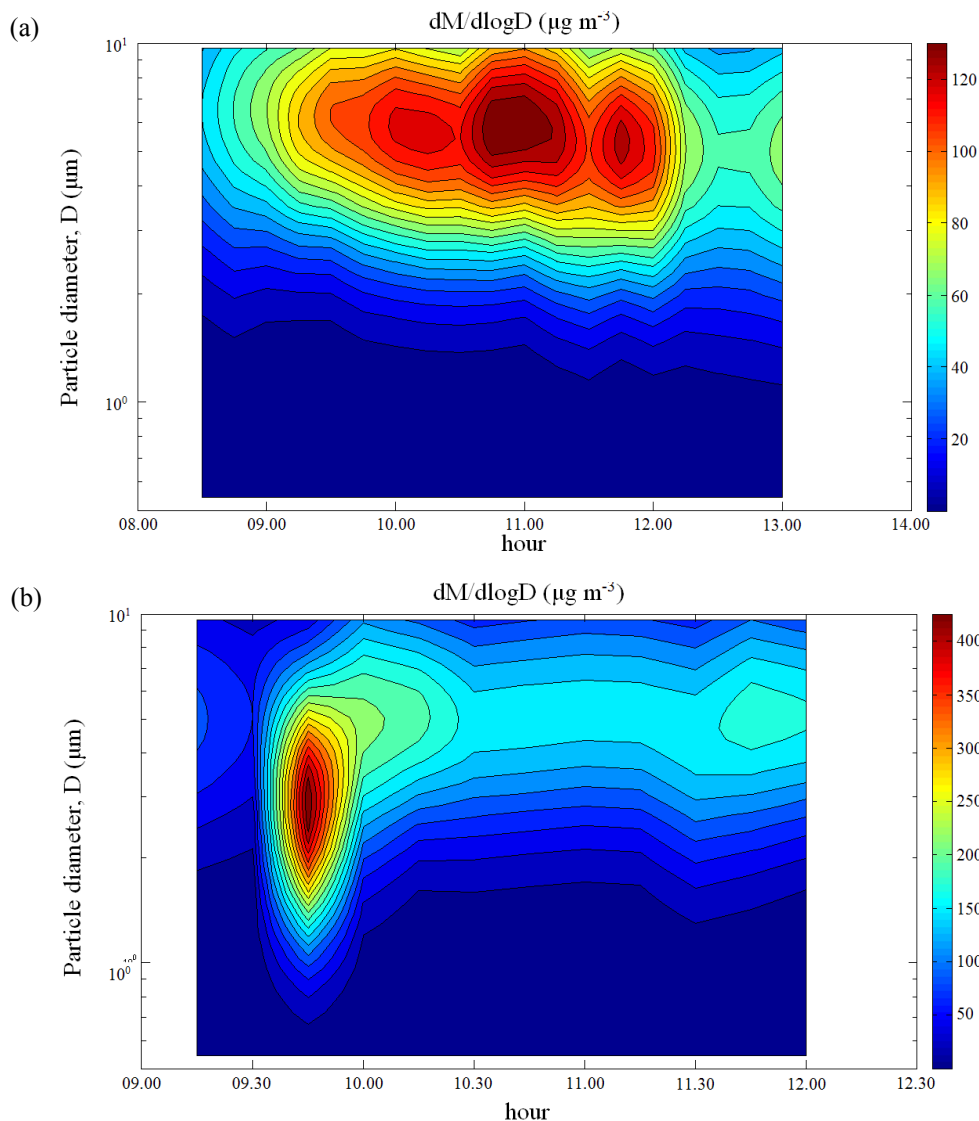

Fig. 2. Particle size mass distributions measured during the school activities through the APS3321: a) G2; b) G3; c) G5; d) G10.
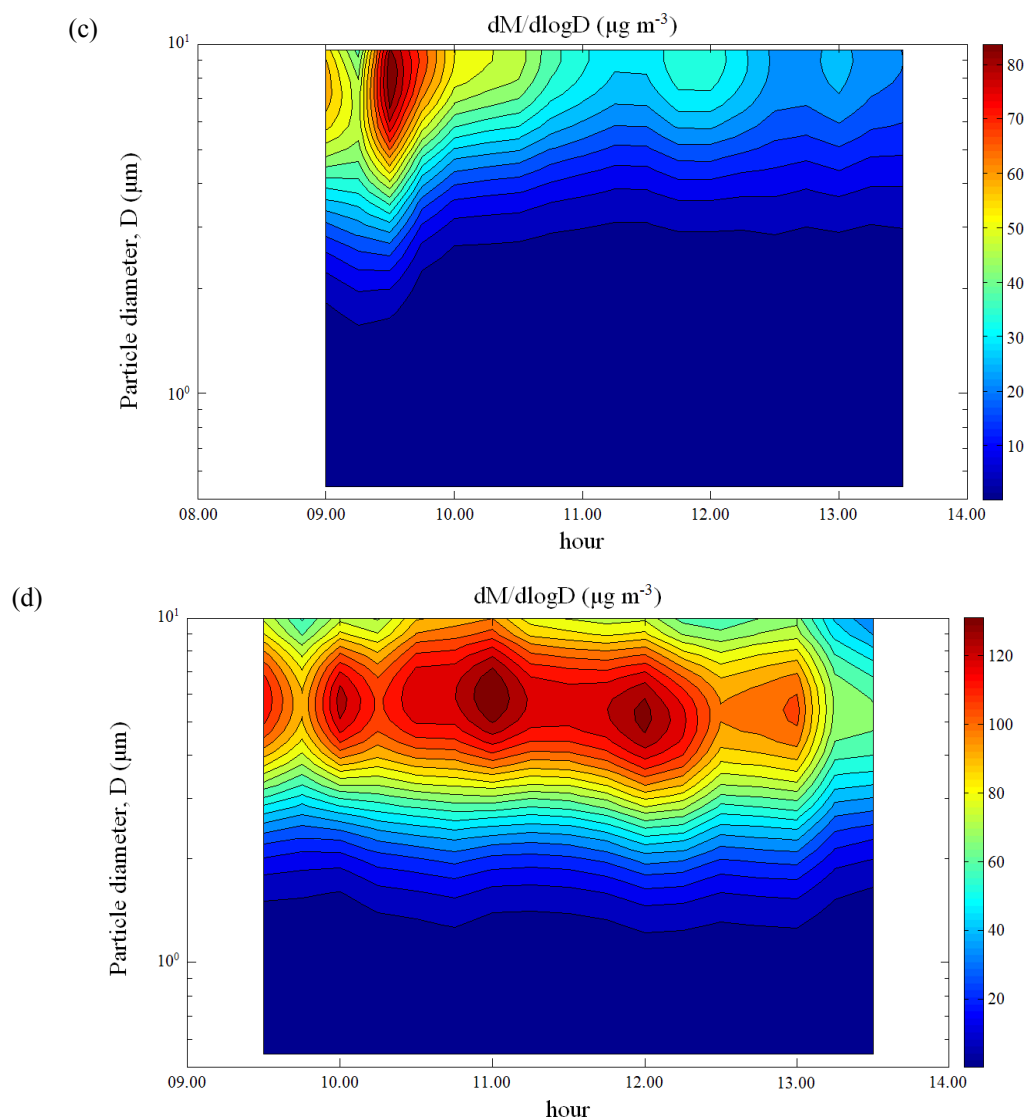
(c)

(d)

Fig. 2. *(continued).*

et al., 2008). Consequently, we applied the methodology described in our previous work (Buonanno *et al.*, 2011b) based on the dosimetry model proposed by the International Commission on Radiological Protection (ICRP, 1994). Mass particle distributions during the period under investigation are reported in Fig. 2(a). The total deposition equation for 10-year old children (normal nose breathers) during moderate exercise was obtained from the ICRP (1994), and an inhalation rate of 1.5 m³/h was considered. During the hour under investigation, average concentrations of 46.9 and 50.4 μg/m³ for $PM_{10–2.5}$ and $PM_{10–1.0}$, respectively, were measured. Total depositions of inhaled $PM_{10–2.5}$ and $PM_{10–1.0}$ fractions for the same period were evaluated as 70.3 and 75.7 μg/h, respectively. In order to quantify this more clearly, a comparison with one hour class in which the children remained seated was performed. In doing this, we considered the background particle distributions, as measured 5–10 min before the beginning of the activities in the school gym, as the ones the children are exposed to when seated during lessons. Moreover the total deposition equation for

a 10-year old child sitting was obtained from the ICRP (1994), and an inhalation rate of 0.38 m³/h was considered. An hour seated in a class leads to a particle concentration of 18.9 and 35.7 μg/m³ for $PM_{10–2.5}$ and $PM_{10–1.0}$, respectively. Total deposition of inhaled $PM_{10–2.5}$ and $PM_{10–1.0}$ fractions under these exposure conditions were evaluated as 5.5 and 8.3 μg/h, respectively. These results clearly show that one hour of physical activity in the G2 gym exposes pupils to $PM_{10–2.5}$ and $PM_{10–1.0}$ concentrations that are 3.2 and 1.9 times higher, respectively, than one hour sitting in a class. This different exposure lead to a huge difference in dose, with that experienced by students during physical activity being 12.9 and 9.2 times higher, respectively, for $PM_{10–2.5}$ and $PM_{10–1.0}$, than that in one hour of sitting in class. This is due to both the higher deposition efficiency and the higher inhalation rate related to physical activities compared to sedentary ones. The estimated doses show that the $PM_{10–2.5}$ fraction has a greater increase during exercise than the total $PM_{10–1.0}$ fraction, and this is because resuspension mainly affects the particle coarse fraction.

PM$_{10-2.5}$ Emission Factor and Outdoor Contribution

Fig. 3 shows the PM$_{10}$, PM$_{2.5}$ and PM$_{10-2.5}$ trends during the monitoring of the G2 school gym, both for indoor and outdoor conditions. The G2 gym was selected as representative of the analyzed schools, as all of them are in the same urban area and the outdoor trends were found to be similar, depending on traffic emissions.

The outdoor PM$_{10}$ and PM$_{2.5}$ show higher values during morning rush hours, and start to decrease at about 9.00 am (Fig. 3(a)). The corresponding indoor trends show an increase during the morning due to the activities of the pupils (Fig. 3(a)). Therefore, PM$_{10}$ and PM$_{2.5}$ indoor-to-outdoor ratios (I/O) were found smaller than 1 during morning rush hours, then becoming greater than 1 as pupil activity increased. Fig. 3(b) shows the coarse fraction measured in the G2 gym during the pupils' activities, and the corresponding outdoor values. This figure shows a significant increase in the indoor coarse fraction during the morning, with the corresponding outdoor coarse fraction presenting negligible variations. Unlike the PM$_{10}$ and PM$_{2.5}$ trends, PM$_{10-2.5}$ I/O were always higher than 1.

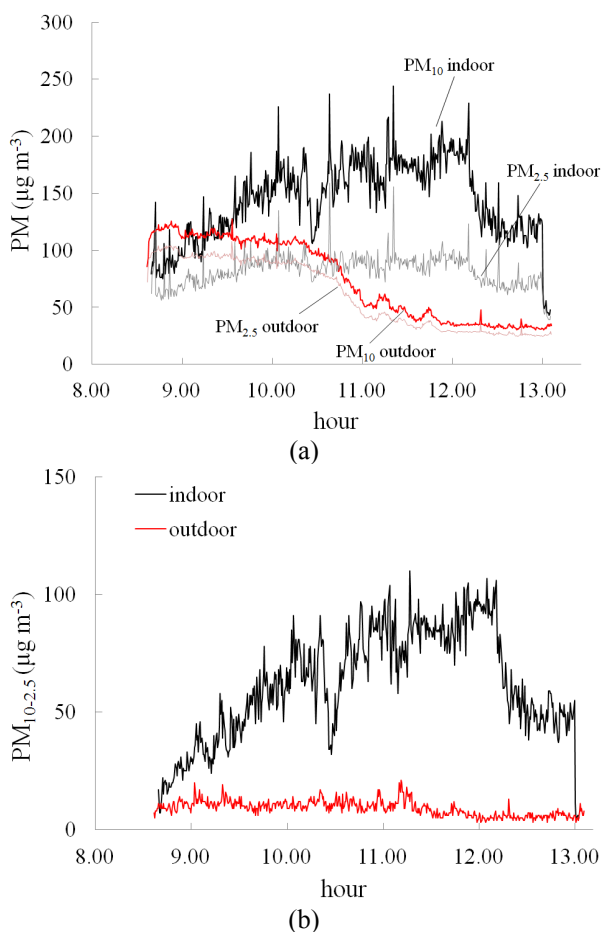The indoor resuspended particle concentration can also be influenced by outdoor PM$_{10-2.5}$, and thus it is worth estimating the outdoor coarse particle contribution to the indoor one. On the basis of the measured PM fractions and Air Exchange Rates (AERs) reported in Table 2, a slight increase in mean indoor PM$_{10-2.5}$ values is found as the AER increases ($R^2 = 0.19$). The contribution of the outdoor PM$_{10-2.5}$ fraction to the indoor one was expected to be insignificant, since no association between the indoor PM$_{10-2.5}$ values and the outdoor ones was found ($y = -0.0006x + 0.6775$; $R^2 = 0.01$). Indeed, by using the emission factor equation (Eq. (2)) along with the PM fraction and AER data reported in Table 2, the contributions of the outdoor to the indoor coarse fraction concentration for each school gym were determined. Values of 1.8%, 5.8% and 6.6% corresponding to the 25th percentile, median value and 75th percentile, respectively, highlight the negligible contribution of the outdoor micro-environment to the indoor coarse fraction. Therefore, the dominant source of coarse fraction in a gym with exercising pupils is the activities that are being done.

Based on Eq. (2), Table 2 shows the coarse fraction emission rates for each school gym. The total emission factor presents a median value equal to 4.7 mg/min, with the 25th and 75th percentiles at 3.0 mg/min and 6.0 mg/min, respectively. In terms of the PM$_{10-2.5}$ emission factor, the activities in the school gyms generate emissions on same order of magnitude as the operation of two gas stoves cooking meat (Buonanno *et al.*, 2009; Lee *et al.*, 2011).

On the basis of the exercising pupils, Table 2 shows the coarse emission factors per pupil, with 37 µg/min/pupil, 67 µg/min/pupil and 70µg/min/pupil at the 25th percentile, median value and 75th percentile, respectively.

Correlation between Coarse Particle Resuspension and CO$_2$ Concentration

As reported in the previous paragraphs, the particle resuspension, and thus the PM concentrations, can be mainly related to the number and type of activity of the students in the school gym. Therefore, a rough correlation can be found between the particle resuspension in the school gyms and the total energy used by the students. Indeed, the human metabolism varies the amount of energy used in each activity. In particular, the total specific energy (E) used by the students, normalized to their body surface area, (J/m^2), can be related to the metabolic rate (MR) associated with an activity (W/m^2) according to the formula:

$$E = \sum_{i=1}^{M} N_i \cdot \dot{MR}_i \cdot \theta_i \tag{3}$$

where M is the total number of the activities performed per hour, N_i is the number of students performing an activity, and θ_i is the time considered (s). The metabolic rates for each activity were derived from Ainsworth *et al.* (2011) and customized for the pupils in this study according to the Harris-Benedict equation (Harris and Benedict, 1918).

As example, Fig. 4(a) shows the correlation between the hourly energy used in the activities carried out by students in the school gym G2 and the corresponding increase in the indoor coarse particle concentration compared to the outdoor value. As expected, if the energy used increased

Fig. 3. (a) PM$_{10}$ and PM$_{2.5}$ trends in the G2 gym during the activities of the pupils and outdoor, (b) PM$_{10-2.5}$ trend in the G2 gym during the activities of the pupils and outdoor.

then an increase in the particle resuspension was observed in a naturally ventilated school. This correlation could depend on several parameters, such as ventilation, floor and walls materials, volume and shape of the gym, although it is typical of each school gym analyzed in this work. Fig. 4(b) shows the increase in indoor CO_2 concentration, compared to the outdoor one, as function of the increase in the indoor coarse particle concentration in the school gym G2. The graph demonstrates that the larger the increase of the indoor coarse particle concentration, the greater the rise in the indoor CO_2 concentration. This is as expected for naturally ventilated school gyms, since CO_2 is a by-product of metabolic activity, and thus the energy used by the students is related to the amounts of both CO_2 and $PM_{10-2.5}$.

In order to generalize the results, Fig. 5 shows the increase in indoor coarse particle concentration in comparison with the outdoor values vs. the corresponding increase in CO_2 for all the school gyms analyzed in this work. The trend of $PM_{2.5}$ concentration as function of CO_2 concentration was analyzed in order to normalize the data with regard to school gym volumes and air exchange ratios. The good correlation shows that for a variation of 100 ppm of CO_2 due to metabolic activity in a naturally ventilated school gym, a corresponding increase of about 13 $\mu g/m^3$ in the coarse PM fraction was found. For the case examined in this study, the measurement of the CO_2 concentration could be a useful proxy to estimate the contribution of the physical activities of pupils to coarse particle exposure in naturally ventilated school gyms.

CONCLUSIONS

In this study, different particulate matter concentrations and distributions in the super-micrometer range were measured in 12 school gyms during a 3-month experimental campaign in order to evaluate exposure in this micro-environment. Particulate matter concentrations showed great variation as a function of the school gym: and the corresponding maximum values were generally much higher than 100 $\mu g/m^3$. High particle mass concentrations were mainly related to the activities that were carried out and the number of pupils. In fact, the outdoor PM fractions presented mean values that were always lower than the corresponding indoor ones, highlighting the presence of an indoor source (i.e., resuspension) due to the activity of pupils. The median coarse particle emission factor was found to be 4.7 mg/min, with a corresponding coarse emission factor per pupil of 67 $\mu g/min/pupil$. By monitoring particle mass distribution vs. time, relevant peaks were related to the activity of students, revealing a strong correlation between particle resuspension and the number of students and their activities.
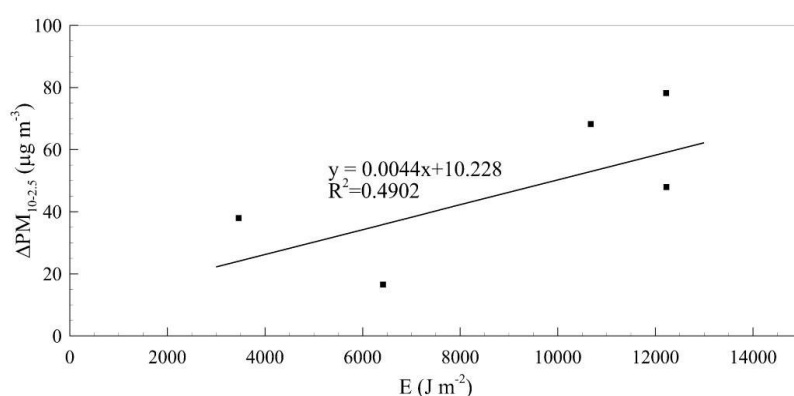

Fig. 4(a). Hourly energy used in the activities carried out by students (E) in the school gym G2 vs. the corresponding increment of the indoor coarse particle concentration compared to the outdoor value.
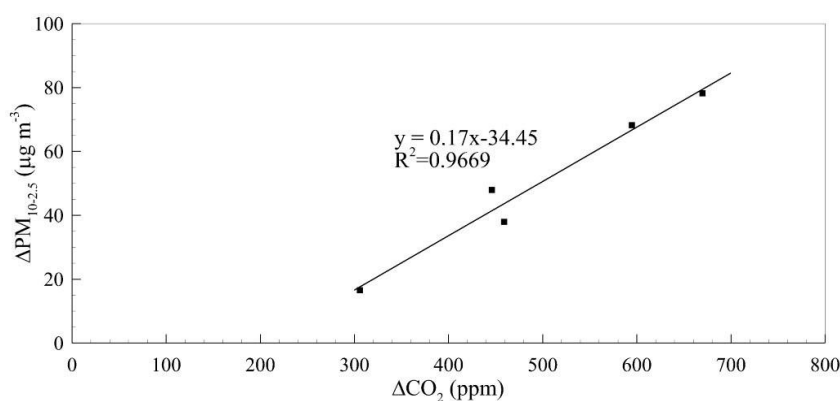

Fig. 4(b). Hourly indoor CO_2 concentration, compared to the outdoor one, in the school gym G2 vs. the corresponding increment of the indoor coarse particle concentration, compared to the outdoor value.
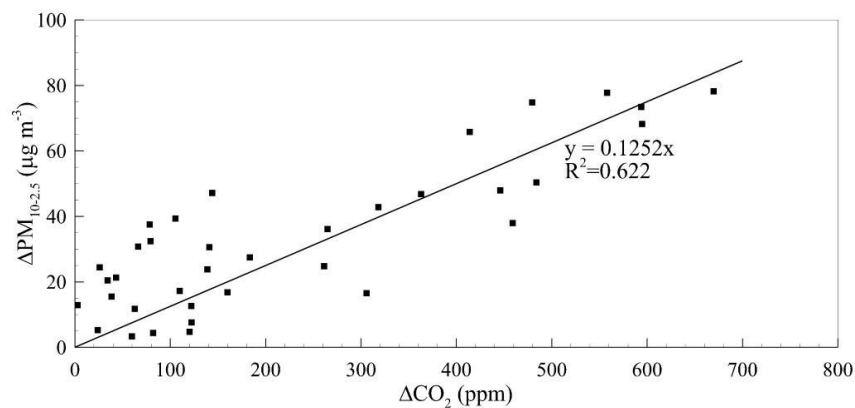
Fig. 5. Hourly increment of indoor coarse particle concentrations, compared to the outdoor one, vs. the corresponding increments of CO_2 for all the school gym analyzed.

The coarse particle dose (total deposition of inhaled $PM_{10-2.5}$ fraction) for a 10-year old child during one hour of physical activity was evaluated as 70.3 µg/h, which is 12.9 times higher than the dose they would experience if seated in class.

As expected, if the energy used increases, a rise in particle resuspension is observed in a naturally ventilated school gym. Meanwhile, the indoor CO_2 concentration (considered a by-product of metabolic activity), compared to the outdoor one, is expected to increase in naturally ventilated school gyms along with the energy used.

The increase in the indoor coarse particle concentration with respect to outdoor values vs. the corresponding increases in CO_2 for all the school gyms was also analyzed. This was carried out in order to generalize the results by normalizing the data for the gym volumes and air exchange ratios. A variation of 100 ppm of CO_2 due to metabolic activity in a naturally ventilated school gym corresponded to an increase of about 13 µg/m^3 in the coarse PM fraction. Consequently, the measurement of CO_2 concentration could be a useful proxy in order to estimate the contribution of physical activity to the coarse particle exposure in naturally ventilated school gyms.

Although the results presented in this work are limited to an Italian case-study, they provide useful data on the exposure of students to airborne particles during periods of physical activity. In addition, the results can also be extrapolated to schools with natural ventilation, which are common in many countries.

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