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Assessment and improvement of indoor environmental quality in a primary school

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This study reports levels of indoor environmental quality variables before and after installation of heat recovery ventilation in a primary school located in an urban area in Izmir, Turkey. A CO_2-based modeling was performed to determine the required flow rates that would comply with an international ventilation standard, followed by computational fluid dynamics modeling for best airflow distribution in a classroom. Temperature, CO_2, $PM_{2.5}$, and total volatile organic compounds were found at undesired levels, among which relative humidity, CO_2, and $PM_{2.5}$ were improved after the intervention. Reductions in the mean and maximum concentrations were 29% and 68% for CO_2 and 29% and 46% for $PM_{2.5}$. This intervention study was a part of the city-wide main project that aimed to increase awareness of the students and their families, teachers, and staff regarding importance of indoor environmental quality in both at school and home due to its possible effects on children's health and academic performance, one of the major challenges of today's societies all around the globe.

Introduction

School buildings, including daycares and kindergartens, are one of the most important indoor environmental quality (IEQ) issues today because (1) children spend the most of their time in these buildings second to home; (2) high population density, poor ventilation, lack of maintenance, and unsatisfactory cleaning are common, and there are unique sources of pollution leading to very high pollutant concentrations compared to outdoors (Daisey et al. 2003; de Gennaro et al. 2014; Mendell and Heath 2005); and (3) children are sensitive and susceptible to the environmental effects not only because they are still growing (Faustman et al. 2000) but also due to their physical activity and behavior (Annesi-Maesano et al. 2013). Outdoor air is also a source through ventilation and penetration for pollutants which generally have lower indoor source strengths compared to those of outdoors (de Gennaro et al. 2014; Mendell and Heath 2005).

Inorganic gaseous contaminants such as CO, NO_2, O_3, organic gaseous pollutants such as volatile organic compounds (VOCs), bioaerosols, particulate matter (PM), and semi-VOCs that partition between the gaseous and particulate phases are some of the main groups of indoor air pollutants in schools. Ultrafine particles (UFP, particles with diameters $<$100 nm) are reported to be an important PM size group with higher exposure potential due to deep penetration into the lungs and large surface area for biological interactions, source of which are mainly outdoor air (traffic and new particle formation) for schools with no cooking activities (Fuoco et al. 2015). While CO_2 has been considered as an indicator of air exchange, a recent study showed that it may be an indoor air pollutant (Satish et al. 2012).

In addition to acute symptoms such as headache, dizziness, tiredness, eyes–nose–throat–skin irritation, and wheezing, indoor air pollution have been associated with allergic disorders, such as allergic rhinitis, allergic sensitization, atopic dermatitis, and allergic asthma, and diseases such as chronic obstructive pulmonary disease (Annesi-Maesano et al. 2013). Furthermore, academic performance, school absenteeism, scoring in standardized tests, decision making, memory, concentration, error rate have been associated with IEQ and ventilation (Annesi-Maesano et al. 2013; Bakó-Biró et al.

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2012; Haverinen-Shaughnessy et al. 2015; Mendell and Heath 2005; Satish et al. 2012; Shaughnessy et al. 2006; Shendell et al. 2004; Stafford 2015; Twardella et al. 2012).

Consequently, provision of sufficient fresh air through ventilation is critical to sustain school IEQ for the health and success of children. However, it is difficult to use natural ventilation because of number, variety, and strength of pollution sources, and population density. Therefore, mechanical ventilation has commonly been suggested and applied as the solution, which requires pollution control measures for those buildings located in polluted areas such as metropoles and industrial areas. Due to financial restrictions that majority of schools face, heat recovery ventilation (HRV) is considered appropriate for energy and operating cost savings, which may also result in mechanical ventilation becoming source of contamination due to lack of maintenance and cleaning. Nonetheless, occupant behavior is a significant factor that may impact IEQ. Hence, IEQ management requires awareness and involvement of students, teachers, and school management.

Studies conducted in some European countries, the United States, Australia, and countries with specific climatic conditions such as Singapore produced information regarding the significance of IEQ in relation to children's health and academic performance (e.g., cited in Daisey et al. 2003; Mendell and Heath 2005; Wargocki et al. 2002) propagated interest all around the globe where the significance of IEQ have started to be recognized (e.g., Elbayoumi et al. 2013; Halek et al. 2013; Jovanović et al. 2014; Mainka et al. 2015; Mohamad et al. 2016; Sohn et al. 2009) including Turkey (Babayiğit et al. 2014; Demirel et al. 2014; Ekmekcioglu and Keskin 2007; Mentese et al. 2012; Sofuoglu et al. 2010, 2011). In such places, schools are naturally ventilated, and energy-conscious intervention for existing schools will be the main task that should be guided by the scientific studies (such as Norback et al. 2011; Rosbach et al. 2013; Wargocki and Da Silva 2015). Thus, it is crucial for those studies to have a holistic approach.

This study aimed to conduct a pilot study to investigate application of HRV to provide a healthy classroom indoor environment for pupils of an elementary school in a polluted urban environment. IEQ (thermal comfort and indoor air quality [IAQ]) was measured before and after installation of the mechanical ventilation, for which flow rate was estimated by modeling CO_2 in a classroom to design a system that could comply with a selected international standard. Efforts of raising awareness were included (guidebooks were written and distributed to children and teachers/management, seminars were given, and a website, www.iccevrekalitesi.net, was constructed) in the scope of the project but its effects were not measured.

Material and methods

Building location and characteristics

The selected school (Nihat Gündüz Ortaokulu) is located in Işıkkent area in Izmir, Turkey, where there are some industrial facilities such as two cement plants at distances of 2.2 and 3.0 km, and two beer plants 0.7 and 1.0 km away, a household and personal care products plant (1.3 km), many small and medium sized enterprises (SMEs), and a highway and intersection of major roadways (Figure S1 in supporting information [SI]). It houses both elementary and secondary grade levels. Some important information about the school are as follows: A three-floor building with a basement, 16 classrooms, 1 kindergarten, 350 students, 25 teachers, classes from 0840 to 1520 weekdays with 40 min periods, 10 min breaks, and a 1 h lunch break.

A classroom of 30 students, which is located on the ground floor, was selected for IAQ and thermal comfort monitoring, and installation of HRV mechanical ventilation unit. The classroom (L × W × H of 630 × 630 × 290 cm) was occupied by the 4th graders. Monitoring devices were placed in a casing in the middle of the classroom (SI, Figure S2). Classes of the 4th graders started at 0840 and ended at 1420 with 10 min breaks between 40 min periods. A lunch break of 1 h was given after the 4th period.

IAQ monitoring

IAQ monitoring device (Quest EVM-7) was capable of simultaneously monitoring CO_2, NO_2, PM_{10}, and total volatile organic compounds (TVOC). It was placed at the height of 1.1 m at the breathing level of the students (SI, Figure S2). IAQ monitoring was conducted in the classroom for six, 1-week periods in October 2014–January 2015 period before intervention, and for two weeks after intervention. Before intervention, monitoring was also conducted during the weekend of the first week. In addition, two scenarios were run: (1) regular operation in which students left the classroom as they pleased during the breaks; and (2) all students were required to open all the windows and leave the classroom. The device was run daytime starting 20 min. before the 1st period to 2.5 h after the end of the last period. Monitoring was also conducted nighttime for at least 4 h.

The monitoring device measures PM_{10} concentrations by a 90° optical light emitting photometer, and reports in $\mu g/m^3$. Calibration of the device for PM was based on Arizona Street Dust by the manufacturer, so a correction factor was required for reliable results in a specific indoor environment. This correction factor was determined by conducting a preliminary sampling campaign that monitored the PM concentrations and collected the particles on a filter placed into the internal filter holder of the device. Comparison of the mass and counter based concentrations resulted in a factor value of two. TVOC concentrations are measured with a photo ionization detector (PID) in ppb units. CO_2 and NO_2 concentrations are measured in ppm units with a nondispersive infrared (NDIR) sensor. These detectors were calibrated according to manufacturer described methods. Concentrations were measured at 30 s intervals, and reported as 5-min averages.

Thermal comfort assessment

Thermal comfort conditions of students were assessed using both objective measurements and subjective surveys.

Temperature and relative humidity (RH) were measured every 10 min with Hobo U12 devices at the ankle, waist, and head heights for a seated child, which are 0.1, 0.6, and 1.1 m, respectively, according to ASHRAE Standard 55 (2013) in the pilot classroom. Like IAQ monitoring, thermal comfort assessment was conducted in the classroom for six, 1-week periods in October 2014–January 2015 before intervention, and for 2 weeks in February 2015 after intervention. It was observed that students wore warm enough clothes, therefore, assessments were made by accepting the 20°C–24°C temperature range as the comfort range as recommended in ASHRAE Standard 55 (2013). In addition, subjective assessment was made by applying a thermal comfort survey (Teli et al. 2012) to the students of the classroom. A 7-point scale predicted mean vote (PMV) index was used for the survey. In this scale, −3 is cold, −2 is cool, −1 is slightly cool, 0 is neutral, +1 is slightly warm, +2 is warm, and +3 is hot. A school-wide subjective inquiry was performed in a total of 14 different classrooms during the months of December and January, whereas after intervention it was administered in two classrooms for 3 days in February, where the mechanical ventilation was installed. Days with very low outside temperatures were carefully selected for the application of the survey in order to assess the most negative thermal comfort conditions for the school. The same questions were asked in different ways to achieve cross-examination and the most accurate results. The students were asked about their clothing to identify unusual responses due to clothing, which were then eliminated. Responses to cross-examination questions were compared, and inconsistent answers were eliminated.

Mechanical ventilation design

CO_2 modeling for determination of ventilation rate

Ianniella (2011) compared ventilation standards applicable for school buildings in the European Union (EU), Finland, France, the Netherlands, Portugal, the United Kingdom, and the United States. These standards recommend minimum fresh air per person and/or per unit area, and maximum CO_2 concentration individually or in combination. Both types are considered in detail in Building Bulletin 101 of the United Kingdom requiring a minimum of 3 L/s/p which can be increased to 8 L/s/p when needed, and keeping CO_2 concentration (1) below 1500 ppm for periods of without a long break; (2) below 5000 ppm during the school day; and (3) CO_2 concentration can be reduced below 1000 ppm at any time (BDE 2006). Therefore, this standard was selected to comply with. As a result, indoor air CO_2 concentration in the pilot classroom was modeled to determine the design flow rate for the mechanical ventilation to be installed. A CO_2 mass balance (Equation 1) as it was recently used by Kalema and Viot (2014) was employed to model the concentrations for different flow rates that would ascertain compliance with the standard. Equation 1 can be solved for constant flow rate, inlet concentration, and CO_2 production rate (Equation 3) for a given time period as in Equation 2.

$$V\frac{dC}{dt} = G(t) + Q\left(C_{inlet} - C(t)\right) \quad (1)$$

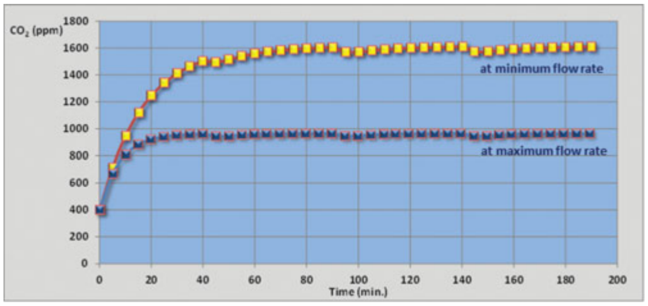

Fig. 1. Modeled pilot classroom CO_2 concentrations at minimum and maximum flow rates.

$$C(t) - C_{inlet} + \frac{G(t)}{Q} + \left[C(0) - C_{inlet} - \frac{G(t)}{Q}\right]e^{-nt} \quad (2)$$

$$G = RQ\frac{0.00276\,A_{Du}\,M}{0.23RQ + 0.77} \quad (3)$$

$$A_{Du} - 0.202\,W_b^{0.425}\,H_b^{0.725} \quad (4)$$

where Q is flow rate, V is volume, $n = Q/V$ is the air change rate, $C(0)$ and C(t) are indoor air concentration at time t = 0 and t = t, G is CO_2 production rate, RQ is the respiratory quotient assumed as 0.83, M is metabolic rate assumed as 1.2 for sedentary activity in schools, A_{Du} is human body surface area estimated using DuBois equation (Equation 4), where W and H are body weight and height. The following values were used in the model: classroom dimensions as 6.3 × 6.3 × 2.9(h) m, number of people as 31 (30 students + a teacher) during the classes and 30 students during the breaks, student body weight, height, and metabolic rate as 32.4 kg, 1.38 m, and 1.2 met, respectively, class and break lengths as 40 min periods and 10 min breaks, and number of periods without a long break as four classes before the 1 h lunch break.

The modeling has shown that CO_2 concentrations are kept below the levels indicated in the standard (see Figure 1) when the flow rate is 3.7 L/s/p (413 m^3/h) at the minimum and 8.0 L/s/p (893 m^3/h) at the maximum, even when everybody (except for the teacher) remain in the classroom during the 10 min breaks.

Computational fluid dynamics (CFD) modeling

Three-dimensional (3D) simulations has given us the opportunity to investigate every case in detail and find the most proper solution for ventilation. Unlike the simplified 3D simulation predecessors (Mizuno and Warfield 1992; Murakami, 1997; Murakami et al. 1998, 2000), one of the most detailed and earliest 3D investigations about ventilation of an occupied space in the literature were proposed by Abanto et al. (2004). The results of these studies showed that 3D modeling is a very important tool for obtaining the proper ventilation design. 3D IAQ simulations for classrooms are also proposed in the literature, such as two recent studies on energy efficiency and classroom air environment (Wang et al. 2014a, 2014b). They represented the occupants as rectangular prisms in their

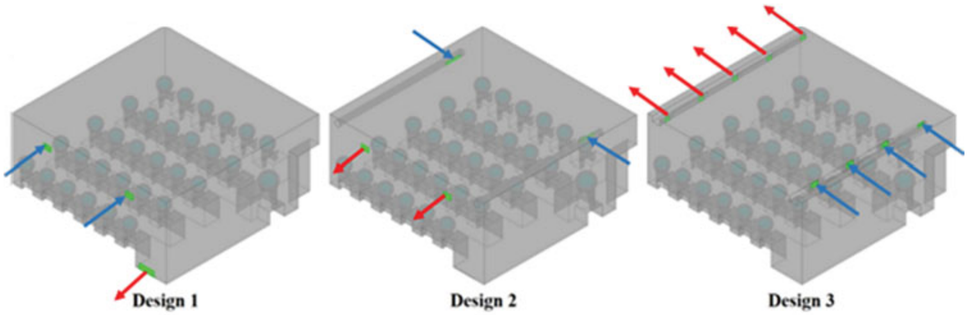

Fig. 2. Investigated ventilation scenarios.

model and reported the temperature, velocity, and CO_2 concentration distributions to analyze the ventilation effectiveness. Kosonen and Mustokallio (2015) compared different mechanical air distribution systems via 3D computer simulations. They used cylinders to represent the occupants in the classroom and visualized the velocity distribution inside the classroom.

CFD modeling was also used in this study to investigate airflow in the classroom. Three different mechanical ventilation system designs all with heat recovery systems (Figure 2) were compared by 3D CFD analyses to have an efficient ventilation inside the classroom. The first design is the simplest one with two inlets on the wall on the corridor side of the classroom and a transfer grill on the door as an outlet. The second design was more complex with two air inlet grills on two cylindrical inlet ducts which are positioned along opposing upper edges of the classroom parallel to each other. Inlet grills for this design are aligned so as to send air into the classroom inclined from the ceiling. Outlet grills are positioned at the positions of the inlet grills of the first design. The third design is the most detailed one with four inlets and five outlets. Inlets are positioned so as to direct air along the aisles between the desk columns, and outlets are positioned along the opposite edge of the inlet duct aligned with the heads of the students at the end of the each column.

Students and the teacher sit alone on their chairs. The space under the desk is assumed to be covered by the legs of the students so that there is not any flow under the desk. Bodies of the students are modeled as cylinders with oval cross-section, and their heads were modeled as spheres which are partly overlapped with the bodies. Geometric details of the students such as legs, arms, hands, etc., were not modeled for decreasing computational cost. The teacher is also modeled at sitting position in a similar manner. All the remaining devices and furniture were not modeled except for the ventilation ducts and the bookshelf. Dimensions of the model are given in Figure 3.

Although 3D simulations produce incomparably more and high-quality data compared with the two-dimensional (2D) simulations, their results are mostly presented in a 2D manner in the literature. Different than the previous numerical studies in the literature, spherical air regions were defined around the heads of the occupants to be able to investigate the flow and other IAQ parameters in detail. These spherical air regions are imaginary surfaces inside the air which have no effect on the flow but can be used to visualize and calculate the air quality and comfort indicators around the occupants heads. Therefore, in this study an alternative representation of the results of IAQ calculations for a classroom is presented.

Total fresh air is distributed to the inlet grilles equally. Designs 1 and 2 have two inlet ports that are fed by separated ducts which are located at the outside of the classroom. A 44° diverging inlet grill with three separated parts (22°/0°/–22°) was selected to diffuse the fresh air into the classroom properly in all designs. In addition, vertical directing guides were used to direct the flow downward into the classroom. Therefore, angular orientation of the fresh airflow at the inlets was also defined in the numerical study. There is a suction fan at the outlet port of the heat recovery system for Designs 2 and 3. The suction effect was included in the numerical study by defining −20 Pa relative pressure to the outlets. Exhaust air is free to leave the classroom in Design 1 so the relative pressure

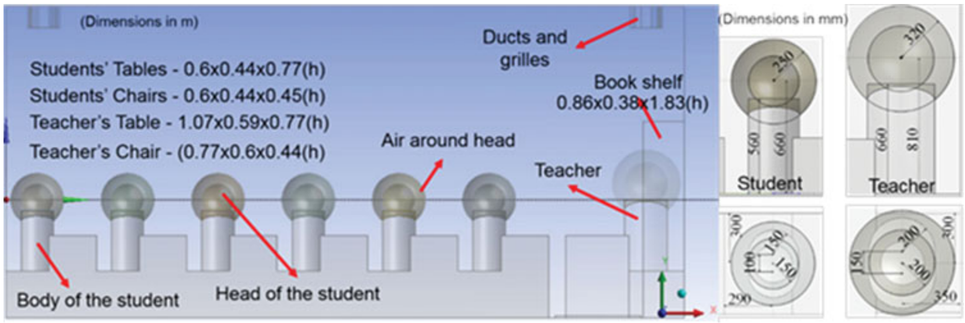

Fig. 3. Details of the investigated geometry.

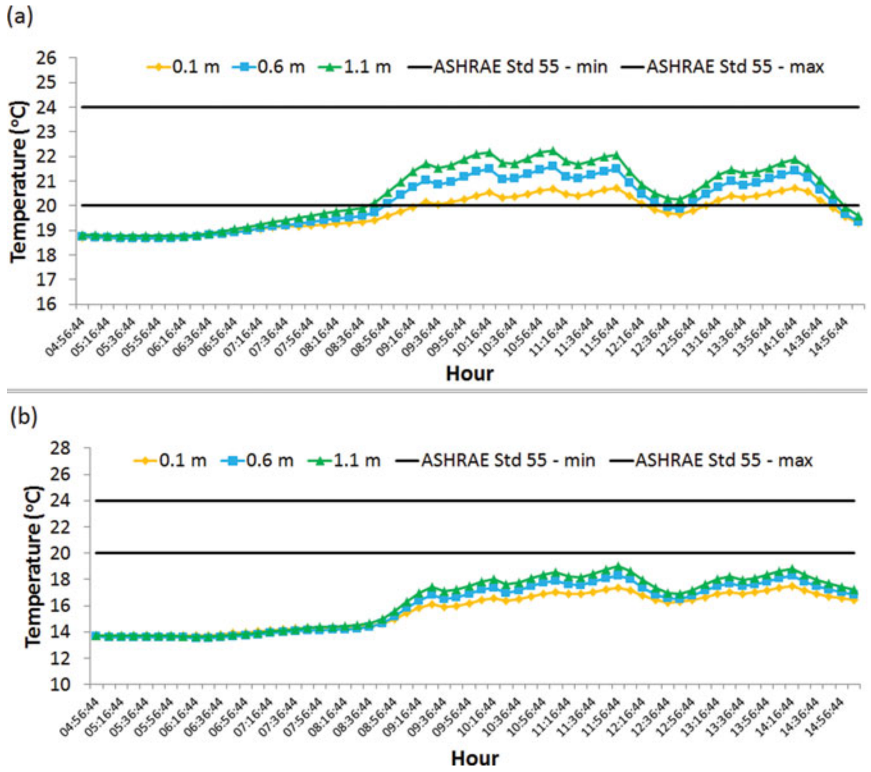

Fig. 4. Diurnal variation in the mean temperature in the pilot classroom in a. December; and b. January.

was 0 Pa at the outlet. The windows are assumed to be closed and classroom is perfectly insulated to any infiltration. Heat transfer is not modeled and turbulence effects are calculated by using k-ε turbulence model.

A commercial software (ANSYS CFX) was used to build the model, define boundary conditions, discretize the solution domain, and solve the corresponding governing equations. Steady Reynolds Averaged Navier Stokes equations were solved with an additional differential equation describing the transport of the scalar “mean age of air” (MAoA). The steady method for calculating MAoA was used due to the proved compromise between accuracy of results and computation time (Chanteloup and Mirade 2009).

To calculate the transport of the scalar “ϕ”, one additional convection diffusion equation needs to be solved with the following general form:

$$\frac{\partial\left(\rho\phi\right)}{\partial t}=\nabla\cdot\left(\rho\overrightarrow{V}\phi\right)+S_{\phi} \tag{5}$$

where t is time, ρ is the density, D is the kinematic diffusivity of the scalar, $\overrightarrow{V}$ is the average velocity that the quantity is moving, S_{ϕ} is the source term that defines the source or the sink of the scalar. For steady flows Equation 5 is simplified to:

$$\nabla\cdot\left(\rho\overrightarrow{V}\phi-\rho D\nabla\phi\right)=S_{\phi} \tag{6}$$

The source term is taken as equal to 1 (Bartak et al. 2002; Chanteloup and Mirade 2009; Gan 2000; Hu and Chuah 2003). Kinematic diffusivity of the scalar includes both laminar and turbulent components as:

$$D=\frac{\mu}{\sigma_{l}}+\frac{\mu_{\mathrm{t}}}{\sigma_{t}} \tag{7}$$

where μ and μ_{t} are the physical and turbulent viscosity, σ_{l} and σ_{t} are laminar and turbulent Schmidt numbers, respectively. As the solution is turbulent in this case, laminar component will have a poor effect compared to the turbulent one, because turbulent viscosity is higher compared to the laminar viscosity (Chanteloup and Mirade 2009). For turbulent flows, in ANSYS CFX, the turbulent diffusion is included in the solution by default as a consequence of averaging the advection term. Therefore, the kinematic diffusivity is not defined but included in the solution. The boundary conditions for the solution of Equation 2 are a zero value at air inlets and outlets (in case of return flow), as given in the literature (Bartak et al. 2002; Chanteloup and Mirade 2009; Gan 2000; Hu and Chuah 2003).

Results and discussion

Thermal comfort

Diurnal variation in the mean temperature values measured in the classroom in December and January are presented in Figure 4. Figure 4a show that in December both of the thermal comfort variables were in the recommended ranges indicated in the figure. Furthermore, it can also be seen from

Table 1. Subjective thermal comfort survey results for December and January 2014.

	December			January		
Classroom	T(°C)	RH (%)	Mean PMV	T(°C)	RH (%)	Mean PMV
1	21.4	46	+0.05	14.0	49	− 3.00
2	19.4	41	− 1.44	15.0	50	− 1.28
3	24.0	38	+0.86	24.0	42	− 0.50
4	21.8	36	− 1.63	18.0	50	− 0.79
5	25.0	35	+0.36	15.1	53	− 3.00
6	28.0	44	+0.87	15.0	39	− 2.40
7	24.0	44	+0.59	15.8	50	− 2.93
8	26.5	38	+1.80	18.7	52	− 0.55
9	17.5	43	− 1.11	17.5	48	− 1.68
10	23.0	44	+1.00	17.3	53	− 2.05
11	21.3	43	+0.89	16.0	43	− 2.76
12	22.6	36	+0.73	18.0	39	− 0.92
13	19.0	48	− 0.27	21.2	43	+0.29
14	20.0	41	− 0.22	21.0	31	− 0.79
Mean	22.4	41.2	+0.18	17.6	45.9	− 1.66
Standard deviation	2.95	4.04	+0.97	2.85	6.51	1.10
Minimum	17.5	35	− 1.63	14.0	31	− 3.00
Maximum	28.0	48	+1.80	24.0	53	+0.29

PMV: predicted mean vote.

Figure 4a that the difference between the ankle and the head levels was not more than 3°C, which is the recommended value for thermal comfort in the relevant standards. In January on the other hand, the temperature values were never in the comfort zone, and time to time they were much lower than the indicated thermal comfort limit (Figure 4b). RH was within the 50%–60% range in both December and January which influence on thermal comfort is rather limited at these temperature and metabolic activity levels as mentioned in ISO 7730 (2005). Results of the survey performed on December 22, 2014 when the outside temperature was 9.1°C are given in Table 1. The temperature in the school varied between 17.5°C and 28°C depending on the classroom, while RH varied between 35%–48%. The average temperature and RH values in the school were found as 22.4°C and 41.2%, respectively. Under these conditions, the PMV value varied between -1.63 and $+1.80$, and the average PMV in the school was $+0.18$. As a result, it can be claimed that subjective assessments were in agreement with the temperature and RH measurements performed in the pilot classroom in December. Results of the survey performed on January 8, 2015 when the outside temperature was quite low are also listed in Table 1. Temperature and RH in the school varied from 14°C to 24°C and from 31% to 53%, respectively, among the classrooms. The average temperature and RH values in the school were found as 17.6°C and 45.9%, respectively. Under these conditions, the PMV value varied between -3 and $+0.29$, while the average PMV in the school was -1.66. Therefore, subjective assessments were in agreement with the temperature and RH measurements performed in the pilot classroom in January, which sometimes fall out of the comfort range.

IAQ

The measured NO_2 concentrations were generally below the device detection limit of 0.1 ppm, therefore, not reported here. Overall average concentrations of the school hours and nighttime were calculated. The mean schooltime concentrations of the 6 weeks for TVOC, $PM_{2.5}$, and CO_2 ranged from 104 to 222 ppb, 240 to 666 $\mu g/m^3$, and 958 to 3775 ppm, respectively. The respective overall average concentrations (±standard deviation) were calculated as 161 ± 50 ppb, 452 ± 177 $\mu g/m^3$, and 2009 ± 993 ppm. The overall averages for the nighttime were lower as 125 ± 27 ppb, 402 ± 208 $\mu g/m^3$, and 539 ± 177 ppm. A higher 24-h maximum CO_2 concentration (5900 ppm) was measured in five classrooms in Hong Kong (Lee and Chang 2000). Babayiğit et al. (2014) investigated IAQ in 172 classrooms of 31 primary schools in Ankara, Turkey, from November 2008 to May 2009. Lower average CO_2 and similar NO_2 levels were measured as 717 ppm and 0.6 ppm, respectively. Fuoco et al. (2015) reported a slightly higher mean CO_2 concentration in winter (from November 2014 to March 2015) as 2206 ± 696 ppm, but a similar level (908 ± 330 ppm) in spring in six naturally ventilated classrooms in Cassino, Italy. Similar average CO_2 concentrations (1500–3130 ppm) were measured in the heating season in central Italy but again average concentrations were lower (<1000 ppm, except one classroom) in the nonheating season, claimed to be, due to increasing ventilation rate in five naturally ventilated classrooms (Stabile et al. 2016). A lower mean TVOC concentration was found as 95.3 ppb (219 $\mu g/m^3$) in winter of 2004 in Korea (Yang et al. 2009), and much lower 5-day average $PM_{2.5}$ concentrations were reported (~ 14 $\mu g/m^3$) in six French cities (Annesi-Maesano et al. 2012).

The difference between schooltime and nighttime show that while CO_2 concentrations reduce significantly (3.7-fold) due to absence of the students as the source, the reduction in TVOC and $PM_{2.5}$ concentrations were not as sharp (1.3- and 1.1-fold, respectively). Weekday-schooltime average concentrations were also about 3-fold higher for $PM_{2.5}$ and CO_2

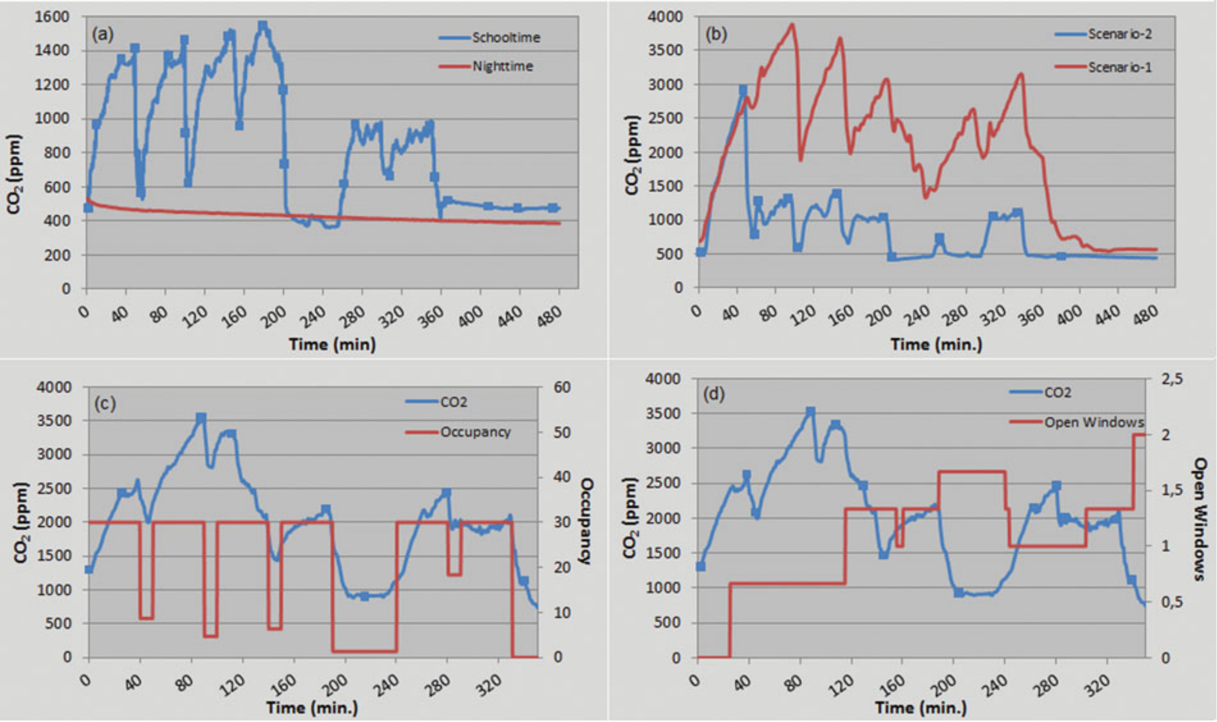

Fig. 5. Average CO_2 concentrations in the classroom a. Comparison of daytime and nighttime; b. In scenario 1 and 2; c. In relation to average number of students; and d. In relation to average number of open windows.

than the corresponding weekend concentrations while they were similar for TVOC. The weekday and weekend night-time concentrations, on the other hand, were similar for TVOC (at about 85 ppb) and CO_2 (at about background levels of 350 ppm) but the mean weekend-nighttime $PM_{2.5}$ concentration (30 µg/m^3) was 9-fold lower than the weekday-schooltime concentration. The above day–night and weekday–weekend comparisons implicate that the main factors that determine $PM_{2.5}$ and CO_2 concentrations are most probably the students and inefficiency of the natural ventilation to reduce the increased concentrations of these two pollutants by the presence of the children (as the emission source by metabolic activity for CO_2 and reentrainment of settled dust by movement for $PM_{2.5}$), whereas TVOC concentrations were probably driven by both the other indoor sources and outdoor sources. A time period, such as a night, would be sufficient to bring down CO_2 but a longer time, such as a weekend, would be required for $PM_{2.5}$ concentrations to come back down.

Figure 5 illustrates the efficiency of natural ventilation by comparing CO_2 concentrations of schooltime and nighttime, Scenarios 1 and 2, and relating the concentrations to the number of students in the classroom. Figure 5a shows that CO_2 concentrations were reduced considerably during breaks, especially in the lunch break to the night-time background levels, while Figure 5b shows that the concentrations can be kept at lower levels by having the children open all the windows and leave the classroom during the breaks (Scenario 2) compared to regular operation (Scenario 1). Figures 5c and 5d show the concentrations along with the number of students in the classroom on two different regular operation days, where windows were mainly open (Figure 5c) and opened only when children felt uncomfortable during the 3rd period (Figure 5d). TVOC levels were also lower in Scenario 2 (144 ± 62 ppb) compared to Scenario 1 (222 ± 141 ppb) indicating that indoor sources might be stronger compared to those of outdoors. On the other hand, comparison of $PM_{2.5}$ concentrations in Scenarios 1 and 2 yielded that they were higher in Scenario 2 (640 ± 431 µg/m^3) with increased natural ventilation compared to regular operation (490 ± 350 µg/m^3) probably due to increased transport of PM from outside. The school is located in a part of the city where it is surrounded by industrial establishments including two cement plants and its quarries, two beer plants, a household—personal care product plant, a number of SMEs, and open fields, in addition to the residential areas (see Figure S1 in SI). It is also located within 500 m of a highway and a junction of major roadways. The current observations hint at major re-entrainment of soil particles from the open fields next to the school especially on windy days. A limitation of this study was that contaminant concentrations could not be measured outdoors, so the ones measured by the municipality of greater İzmir at a close-by station (Bornova, ca. 2 km north of the school) are provided as a general information. The October 2014–January 2015 monthly average concentration ranges of PM_{10} and CO were 37–51 and 446–821 µg/m^3 with overall averages of 45 and 628 µg/m^3, respectively. Average concentrations of February and March 2015 were 35 and 36 µg/m^3 for PM_{10} and 243 and 211 µg/m^3 for CO, respectively.

Figure 5 also illustrates that natural ventilation is generally not sufficient enough to keep CO_2 concentrations below 1000 ppm or 1500 ppm, the two commonly used thresholds

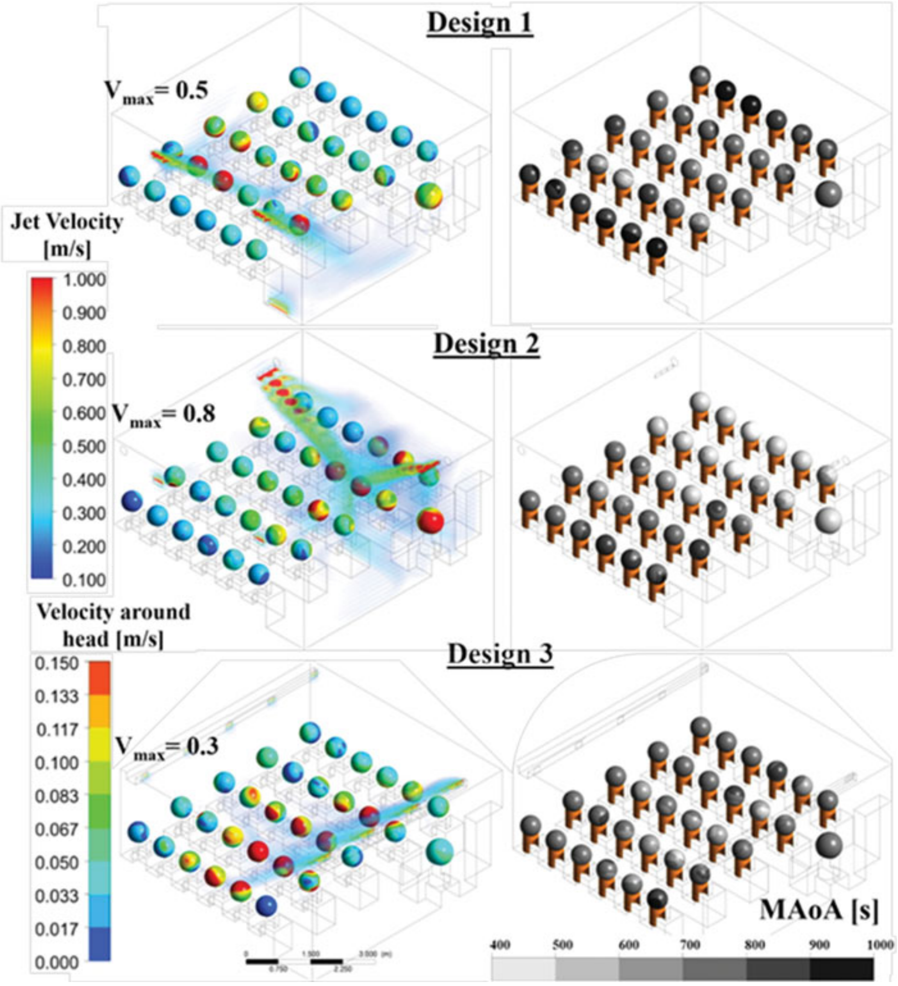

Fig. 6. Comparison of different ventilation designs by means of air velocity and mean age of air (MAoA).

and performance related levels, and unable to keep the concentrations to approach toxicologically relevant levels.

CFD modeling

Three different designs were compared for their ability to satisfy the desired criteria for the maximum allowed air velocity (0.15 m/s) for assuring thermal comfort, occurrence of unventilated or high velocity regions, and MAoA distribution inside the classroom for an airflow rate of 400 m^3/h and blowing angle of 30°. The best design among the three was selected by this comparison.

The velocity distributions on the spherical air regions defined around the heads for different designs are given in Figure 6. The same color scheme with different scales was used to visualize the jet flow inside the classroom and velocity distribution around the heads. Red heads indicate students subjected to draught, whereas blue heads indicate poorly ventilated students. Green heads represent the students which are under comfortable conditions by means of air velocity. For comparison, the number of students subjected to draught seems higher; however, there is air movement nearly all through the classroom in Design 3. When maximum velocity around heads is also taken into account, it is seen that Design 3 has the lowest value which is the desired condition.

Local MAoA values on the spherical air regions defined around the heads are also given in Figure 6 for different ventilation designs. Students at the middle part of the classroom have more fresh air than the students sitting along the sides of the classroom in Design 1. In Design 2, classroom is divided into two parts where there is more fresh air in the window-side half, while Design 3 has the most homogenous fresh air distribution. The maximum, minimum, and standard deviation values of the average MAoA values for every sphere for different designs are given in Table 2. Design 2 has the lowest average value, whereas Design 1 has the highest. As

Table 2. Mean age of air (MAoA) in different designs.

MAoA [s]	Design 1	Design 2	Design 3
Maximum	941	812	876
Minimum	623	486	621
Average	789	655	728
Standard deviation	83	105	48

the fresh air is directed through the aisles inside the classroom in Design 3, the average MAoA value is higher than that of Design 2. Although Design 2 has better values for maximum and minimum MAoA, standard deviation for Design 3 is lower which indicated that the fresh air distribution is more homogenous. Considering the results of the velocity distribution, Design 3 has been selected as the best design of the three.

The selected design was further investigated to discuss the effect of the blowing angle (30, 45, 60, and 75°) and different flow rates (335, 400, 560, and 840 m^3/h) on the ventilation effectiveness and the results were presented in a previous study (Karadeniz et al. 2015).

Application of the intervention

Ventilation

An HRV unit for each classroom was chosen to provide necessary airflow rates calculated according to criteria defined in Building Bulletin 101 as given in the section "CO_2 modeling for determination of ventilation rate." System design (distribution—collection channels, air inlet, and outlet terminals) were designed according to results of the CFD analysis (Design 3) given the previous section (CFD modeling), and applied (Figure S3 in SI).

Ventilation system operates based on demand controlled ventilation. At the beginning of school day, the airflow rate is supplied as the minimum flow rate which provides average CO_2 concentration below 1500 ppm during the day in school. Minimum flow rate is calculated for maximum student number and no student leaving class during the breaks. Daily consecutive lecture number is four. During the day, the flow rate is going to be changed proportionally by the controller according to CO_2 concentration detected by a sensor. A manual control option is also available for maximum flow rate in case of unexpected emission of pollutants.

IAQ

A 2-week monitoring campaign was conducted after the implementation of mechanical ventilation system. The 2-week averages and maximum concentrations are compared here to assess its effect on IAQ. TVOC concentrations were not reduced after the implementation. However, CO_2 and $PM_{2.5}$ concentrations were lower by 29% for both of the pollutants when average values are taken into account, and by 68% for CO_2 and 46% for $PM_{2.5}$ when the maximums are considered. Rosbach et al. (2013) applied a ventilation intervention to 17 primary schools during the heating seasons (October–April) of 2010–2011 and 2011–2012, in which the mean CO_2 level was reduced by 37%. Norbäck et al. (2011) reported a 24% reduction in the mean CO_2 concentration in the schools of mid-Sweden (Enköping) with a modified ventilation system.

The overall schooltime average concentration for CO_2 was 1095 ± 200 ppm. Building Bulletin 101 requires that the average CO_2 concentration over a period without a long break should not exceed 1500 ppm while the maximum value is required to be below 5000 ppm (BDE 2006). The average concentration of the four periods before lunch break is compared with the 1500 ppm standard value. Before intervention, the standard was violated on two regular operation weeks (Scenario 1) with average concentrations of 2658 and 3919 ppm, while it was also violated in one of the two Scenario 2 weeks (1199 and 2985 ppm). The corresponding average concentration after the implementation was 1170 ppm complying with the standard. The maximum concentration during this period was 1680 ppm, which is much lower than those measured before the implementation, although they also never exceeded the 5000 ppm level.

Even three of the 6-weekly average TVOC concentrations (144, 175, and 222 ppb) were higher than the stringer (suggested) standard level of 130 ppb but lower than that of (261 ppb) for offices (Ugranli et al., 2015). The average concentration after the implementation was 184 ppb similar to those measured before the implementation. All weekly average concentrations of $PM_{2.5}$ before the implementation were in exceedance of the American 24-h average ambient air standard concentration (which is applicable to indoor air) of 65 $\mu g/m^3$ (Ugranli et al. 2015). The concentrations after the implementation were reduced (to 295 ± 217 $\mu g/m^3$) but still not below the standard level.

The comparison of before and after intervention is based on measurements performed in different time periods, resulting in confounding by such variables as meteorology, indoor, and outdoor pollutant source strengths, which is a limitation of the study.

Thermal comfort

After the installation of the mechanical ventilation system, a thermal comfort assessment was made in February using a 2-week measurement campaign. Diurnal variation in the mean temperature values in the classroom are shown in Figure 7. Similar to January, the temperature values were always out of the comfort zone, and sometimes much lower than the indicated thermal comfort limit in February. The average RH value was within the 40%–50% range which influence on thermal comfort is rather limited at these temperature and metabolic activity levels as mentioned in ISO 7730 (2005). The available data clearly showed that the capacity of the school's heating system was insufficient to meet the peak load, therefore, unable to increase the temperature in the classroom to the minimum level required for thermal comfort during periods with very low outside temperatures such as in January and February. Considering the outside temperatures were similar, temperature measurements in January, representing before intervention, and in February, representing after intervention, were compared. However, a considerable difference was not observed (see Figures 4 and 7), except for, in contrast to January the temperature in the classroom in February did not drop during breaks when the device was running at the maximum load.

Results of the 3-day surveys performed after intervention in February 2015 are presented in Table 3, during which the outside temperature was quite low. These surveys were performed only in the two classrooms with heat recovery devices installed (the pilot classroom and the neighboring classroom).

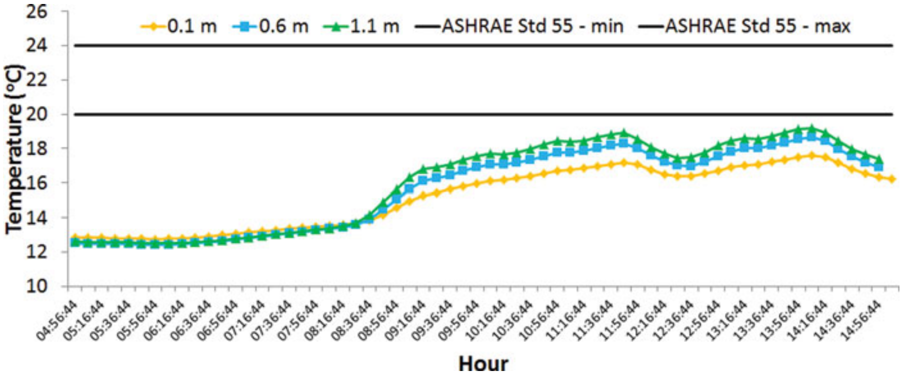

Fig. 7. Diurnal variation in the mean temperature in the pilot classroom in February.

Table 3. Results of February 2015 after intervention thermal comfort survey results.

Date/classroom	T (°C)	RH (%)	Mean PMV
11.02.2015/Pilot	18.0	38	– 0.22
11.02.2015/Neighbor	19.0	40	– 0.04
12.02.2015/Pilot	15.0	50	– 0.88
12.02.2015/Neighbor	14.9	42	– 1.46
17.02.2015/Pilot	14.4	37	– 1.88
17.02.2015/Neighbor	14.6	43	– 1.24
Mean	16.0	41.7	– 0.95
Standard deviation	1.99	4.7	0.72
Minimum	14.4	37	– 1.88
Maximum	19.0	50	– 0.04

PMV: predicted mean vote.

Indoor temperature and RH varied from 14.4°C to 19°C and from 37% to 50%, with the mean values of 16.0°C and 41.67%, respectively. Under these conditions, the PMV value varied between −1.88 and −0.04, while the average PMV was −0.95. Both measurements and the PMV values indicated uncomfortable conditions.

Cross-questions resulted in elimination of 80 out of 251 (31.9%) participant questionnaires in the first survey administered in December, whereas the rate reduced to 47 out of 285 (16.5%) in January, and to 23 out of 168 (13.7%) in February. The decrease in the elimination rate indicates that students started to assess the thermal environment in a more consistent manner.

Conclusion

In this study, results of measurement campaigns of IEQ before and after installation of HRV in a primary school located in an urban area are reported, where some industrial plants (such as cement, brewing, chemical), a highway and an intersection of major roadways, residential areas, open fields are found. A CO_2-based modeling was performed to determine the required flow rates that would comply with an international ventilation standard. Then, CFD modeling was performed to determine the design that would provide comfort in terms of air velocity.

Temperature, RH measurements, and subjective assessment using PMV indicated that there were times when thermal comfort was not attained while IAQ measurements showed that CO_2, TVOC, and PM concentrations in the pilot classroom reached undesired levels due to both indoor and outdoor sources, showing that they cannot be prevented with natural ventilation by simply opening the windows during lecture hours and/or breaks between lectures in classroom. Natural ventilation is also deterred by the outdoor meteorological conditions, especially in cold winter and hot summer months. Installation of HRV unit resulted in considerable reductions in CO_2 and PM concentrations improving IAQ, whereas thermal comfort was still not attained during quite cold days. Although it was not possible to determine whether the heat recovery device was effective since temperatures remained below the limit required for thermal comfort, it was seen that the temperature in the classroom after intervention did not drop during breaks when the device run at the maximum load, which may suggest that the heat recovery device would not adversely affect thermal comfort.

Velocity distribution with steady MAoA distributions obtained by computer simulations provide a basis for selecting between different designs and effect of different parameters on ventilation effectiveness. The CFD analysis may be extended to other designs, and more parameters (CO_2 and other contaminants concentration distribution) might be investigated. The proposed way of representing the 3D data can also be used for calculating the individual flow rates for every occupant, and more specific data can be obtained to determine and define ventilation effectiveness, helping us to find the most efficient way of ventilating a space.

School buildings are deterministically well-defined in function and geometry among others buildings. Most school buildings are built and furnished by government in Turkey by using the same architectural design. Detailed CFD analysis given here is, and the ones to be developed considering sophisticated geometric and thermal models, will be the best tool to have good ventilation effectiveness in classrooms.

This intervention study was a part of the city-wide main project that aimed to increase awareness of the students and their families, teachers, and staff regarding importance of

IEQ both at school and home due to its possible effects on children's health and academic performance, one of the major challenges of today's societies all around the globe. The scientific activity at the school, and presentation of educational seminars were reported by both the students and teachers/managers to improve their knowledge and perception regarding importance of IEQ.

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