Bull Environ Contam Toxicol (2012) 89:898–904
DOI 10.1007/s00128-012-0781-x

Assessment of Fine Particulate Matter and Gaseous Pollutants in Workplace Atmosphere of Metallic Industry

Ülkü Alver Şahin · Birgül Kurutaş

Received: 13 April 2012 / Accepted: 3 August 2012 / Published online: 18 August 2012

Abstract In the present study, we measured the concentrations of fine particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), carbon monoxide (CO) and volatile organic carbon (VOC) in the indoor air of the manufacturing department of a metal factory. The daily average $PM_{2.5}$ concentration ranged between 86.3 and 404.9 μg/m^3. The isolation of the manufacturing machines reduced. $PM_{2.5}$ concentration between 2.5 and 8.8 fold. At the seven measurement points, daily concentrations ranged from 576.7 to 623.4 ppm for CO_2, 0.8 to 15.8 ppm for CO, and 0 to 0.58 ppm for VOC, respectively.

Keywords Indoor air · Air quality · Occupational health · $PM_{2.5}$ · CO · CO_2 · VOC

Research indicates that 32 % of Turkey's population is over the age of 15, which places these individuals in a prime position for employment. Of this labour force, 19.5 % are employed in the industrial sector. This portion of the population devotes an average of 8 h a day to work. The concentrations and types of pollutants in the indoor air of industrial settings change depending on the type of production, the raw materials used during production and the operations utilized during the process.

"Occupational hygiene" is defined as the anticipation, recognition, evaluation and control of workplace hazards (Vincent and Clement 2000). Many studies have examined "occupational hygiene" in the real world. For example, Hsu et al. (2008) observed that employees working in phosphate production facilities were exposed to high concentrations of acid vapour in the form of coarse PM. Sivulka et al. (2007) conducted a literature review regarding nickel concentration in PM that was inhaled by workers in the nickel industry. Kuo et al. (2007) measured $PM_{2.5}$ concentrations and metal contents at three different measurement points in an aluminium smelting facility. During the smelting process, high concentrations of Cr, Cd, Cu, As, Pb, Se, Al and Zn were observed in the facility. Iavicoli et al. (2005) inhaled chemical pollutants in the chemical industry. Demou et al. (2008) reviewed a number of studies that focused on identifying nanostructured particles in an industrial plot plant. The daily mean steady-state concentration of the particles was measured as 188 μg/m^3. Another study by Demou et al. (2009) observed that the average PM_1 and PM_{10} concentrations were 30 and 160 μg/m^3, respectively, in a university machine shop. PM, CO and CO_2 concentrations were investigated at facilities that manufacture and process carbon nanofibers (Evans et al. 2010). Significant CO emissions (47–130 ppm) and respirable particles (1.1 mg/m^3) were observed in the workplace. Though much research has focused on the pure concentrations and exposure rates related to pollutants. Eninger and Rosenthal (2004) observed no association between occupational exposure to $PM_{2.5}$ and heart rate variability in vehicle maintenance workers. Additional research has measured ultrafine particle numbers in the workplace (Elihn and Berg 2009; Evans et al. 2008; Brouwer et al. 2004). To our knowledge, no study has determined industrial indoor air quality in Turkey. Thus, the results of the present study will be an important resource in this field.

Ü. A. Şahin (✉) · B. Kurutaş
Environmental Engineering Department, Engineering Faculty, İstanbul University, 34320 Avcılar, Istanbul, Turkey
e-mail: ulkualver@istanbul.edu.tr

Materials and Methods

In the present study, we investigated a metal processing factory that operates in Istanbul and produces spare parts for the automotive sector. Raw materials that are brought to the factory undergo processes such as cold forming, heat treatment and coating, and after these processes, the product is sent to consumers. In the factory, approximately 1,000 types of bolts are produced, varying in diameter from 2 to 30 mm, and in length from 5 to 200 mm. A settlement plan of the factory and the measurement locations from which the current data were obtained is provided in Fig. 1.

In the cold forming plant, raw materials are directed to appropriate machinery to produce bolts of required dimensions (diameter and length). The machinery manufacture two types of products; one that varies in diameter from 2 to 8 mm (small-diameter), and one that varies in diameter from 8 to 30 mm (large diameter). These products are classified according to their size. Primary production occurs in the cold forming department, and this region of the plant has the highest pollutant issues regarding indoor air quality. Accordingly, the present study was conducted in the cold forming plant. In the cold forming sector, the raw materials are first sent to the manufacturing machines where the shaping process occurs, and it is in this area that the third, fourth and fifth measurement points are located. The machines at the third and fourth measurement points manufacture small-diameter products. Near these machines are three others (the machines numbered one, two and three) that form large-diameter products. The number 15 machine at the fifth measurement point also produces large-diameter products. In this section, there are 18 machines and 40 employees in total. The products that are manufactured in the cold forming sector are directed to threading machines at the sixth measurement point. In this section, there are eight machines operating the same process and 24 workers in total.

After the threading process, the bolts are sent to heat treatment furnaces at the first and second measurement points to be hardened. In this section of the factory, there are two furnaces; one that operates at high capacity and one that operates at low capacity. Both of these furnaces produce high temperatures (700–800°C). Moreover, indoor atmosphere is generated by the use of activated carbon and natural gas to provide the product with necessary hardness. The products from the furnaces are forwarded to the coating section of the factory where seven workers are employed.

The seventh measurement point is located in the quality control department of the factory, whereas the eighth point is located outside the facility to obtain outdoor air measures. There are two offices inside the facility where the ninth and tenth measurement points are located. The factory operates in three 8-h shifts for 24 h a day.

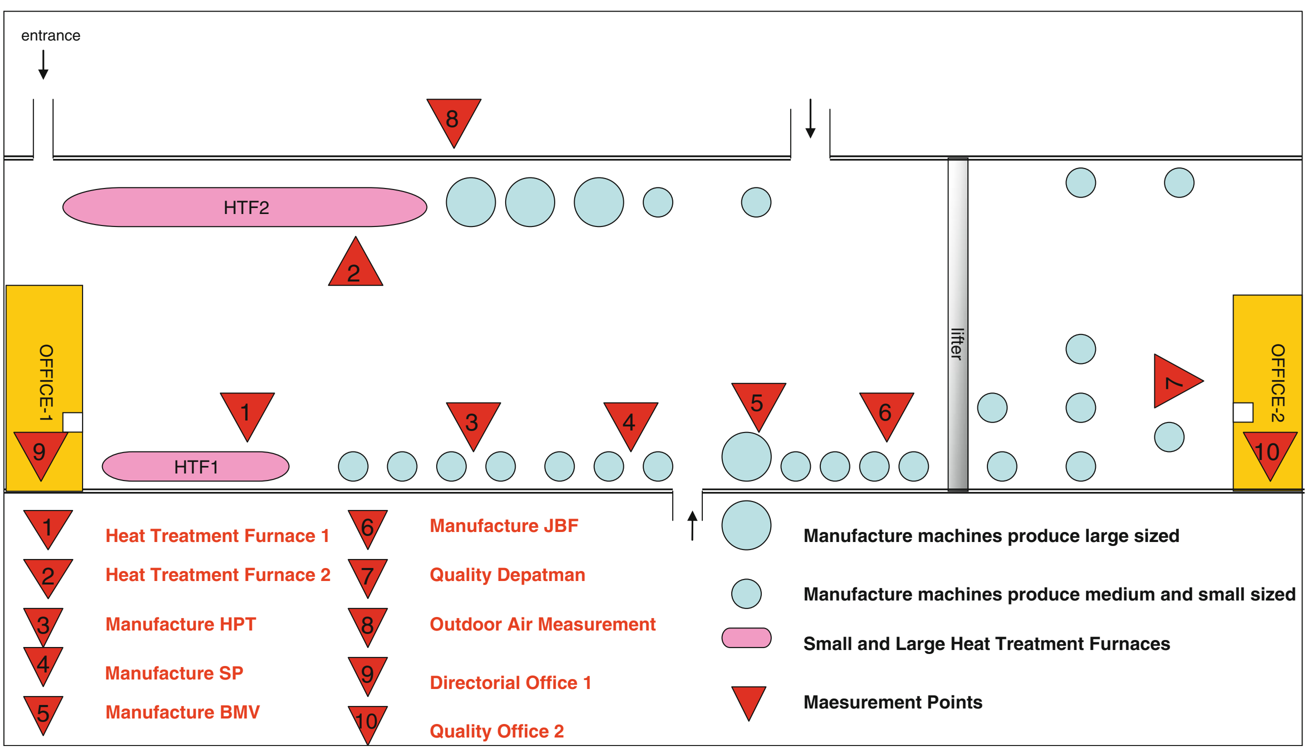

Fig. 1 The factory settlement plan and the measurement points

In the current study, parameters such as temperature, humidity, carbon dioxide (CO_2), carbon monoxide (CO) and volatile organic carbon (VOC) inside and outside the facility were measured with an indoor air quality monitor (IAQRAE) device, and $PM_{2.5}$ concentrations were measured by an MIE DataRAM 2000 device. In the offices, only $PM_{2.5}$ concentration measurements were conducted, using a portable dust measurement device, pDR 1200. In the period between July and August 2008, only $PM_{2.5}$ concentrations were measured, whereas from October to November 2008 and January to February 2009, temperature, humidity, CO_2, CO, $PM_{2.5}$ and VOC were also measured inside the facility. The outside air and office measurements were obtained from October to November 2008 and January to February 2009.

The IAQRAE device is 3,600 g in weight and is easily carried. A photo-ionised detector is used in this device, which allows for the detection of gases in ppm levels. The IAQRAE device can measure CO_2 concentrations in the range of 0–20,000 ppm, CO concentrations between 0 and 500 ppm, and VOC concentrations in the range of 0–10 ppm. Additionally, the device can measure temperatures ranging from 0 to 50°C and humidity in the range of 0 %–95 %. After recharging, the device can operate for 48 h and stores the measured data in its memory. The measurements in this study were recorded at an average interval of 60 s.

$PM_{2.5}$ measurements were obtained using an automatic portable MIE DataRAM 2000 light scattering monitor (manufactured Thermo Inc., USA). The flow rate of the monitor was 1.7–2.3 L min^{-1}. The monitor was placed inside a 0.8 × 0.8 × 1.5 m cabin, which was secured on a platform. The $PM_{2.5}$ measurements were recorded at each measurement location over 6 days, and the average concentrations were recorded every 15 min. Personal exposure to $PM_{2.5}$ inside the offices was measured using a portable real time aerosol monitor; pDR 1200 (manufactured Thermo Inc., USA). The flow rate of the monitor was 4.0 L min^{-1}. The concentrations in each office were recorded during a 3 day period, with an average interval of 30 s during the work day (between 09:00 a.m. and 18:00 p.m.). The validity of the $PM_{2.5}$ values was verified by comparing the $PM_{2.5}$ values obtained from the reference method (EPA RFPS-048-117) to a Thermo Partisol FRM Model 2000 Airsampler. The correlation between the two methods was 0.98.

Results and Discussion

In the current study, seven measurement locations were selected to obtain data on the indoor air quality of the production area (the area where the machines are located) of a metal factory. $PM_{2.5}$, CO, CO_2, and VOC concentrations as well as temperature and humidity levels were measured for at least 8 h and not more than 24 h while considering the working conditions of the facility. Identical measurements were repeated outside the facility to provide a control comparison. In addition, the results were assessed by conducting $PM_{2.5}$ concentration measurements in the two indoor offices of the facility. Natural gas was only used in the heat treatment furnaces at the first and second measurement locations to obtain higher temperatures (700–800°C). The surfaces and ceilings of the buildings were coated with epoxy paint and therefore, did not affect the indoor $PM_{2.5}$ and gas concentrations.

To prevent the formation of dust resulting from the operation of manufacturing machines, isolation system installation occurred between September 2008 and November 2008. Specifically, all of the machines' surroundings were coated with steel sheet metal. The expulsion of dust from the machines to steel sheet metal, with the help of ventilation, was provided. $PM_{2.5}$ concentration measurements were performed under two different conditions; one in which the machines were isolated and one in which they were non-isolated. For each measurement point and in each condition, recordings were obtained for a period of 3 days. The average change of $PM_{2.5}$ concentration during the day at these seven measurement points is illustrated in Fig. 2. The average $PM_{2.5}$ concentration values were evaluated for each point and are summarized in Table 1.

In this section, which housed 26 manufacturing machines and two heat treatment furnaces, measurements for each point were recorded at different days. $PM_{2.5}$ concentrations for the machines with no isolation showed higher alteration depending on the measurement points and time of the record. Changes during the manufacturing process affected $PM_{2.5}$ concentration substantially. Higher concentrations of $PM_{2.5}$ were observed when the small-diameter products were conveyed to the furnaces and when the machines manufactured the large-diameter products. Moreover, elevations in $PM_{2.5}$ concentration occurred when the two heat treatment furnaces were run simultaneously and when unwashed products were carried to the furnaces. Peak $PM_{2.5}$ concentrations were observed at the first run of the machines. The proximity of a working forklift to the measurement point in the manufacturing section also caused an increase in $PM_{2.5}$ concentration. The number of operating machines varies during the day due to the manufacturing process and for technical reasons. At the third and fifth measurement points, where there were many manufacturing machines in close proximity, $PM_{2.5}$ concentrations reached 1,000 $\mu g/m^3$ when all non-isolated machines were being operated.

As can be observed in Fig. 2, $PM_{2.5}$ concentration at each point increased and decreased on a regular basis

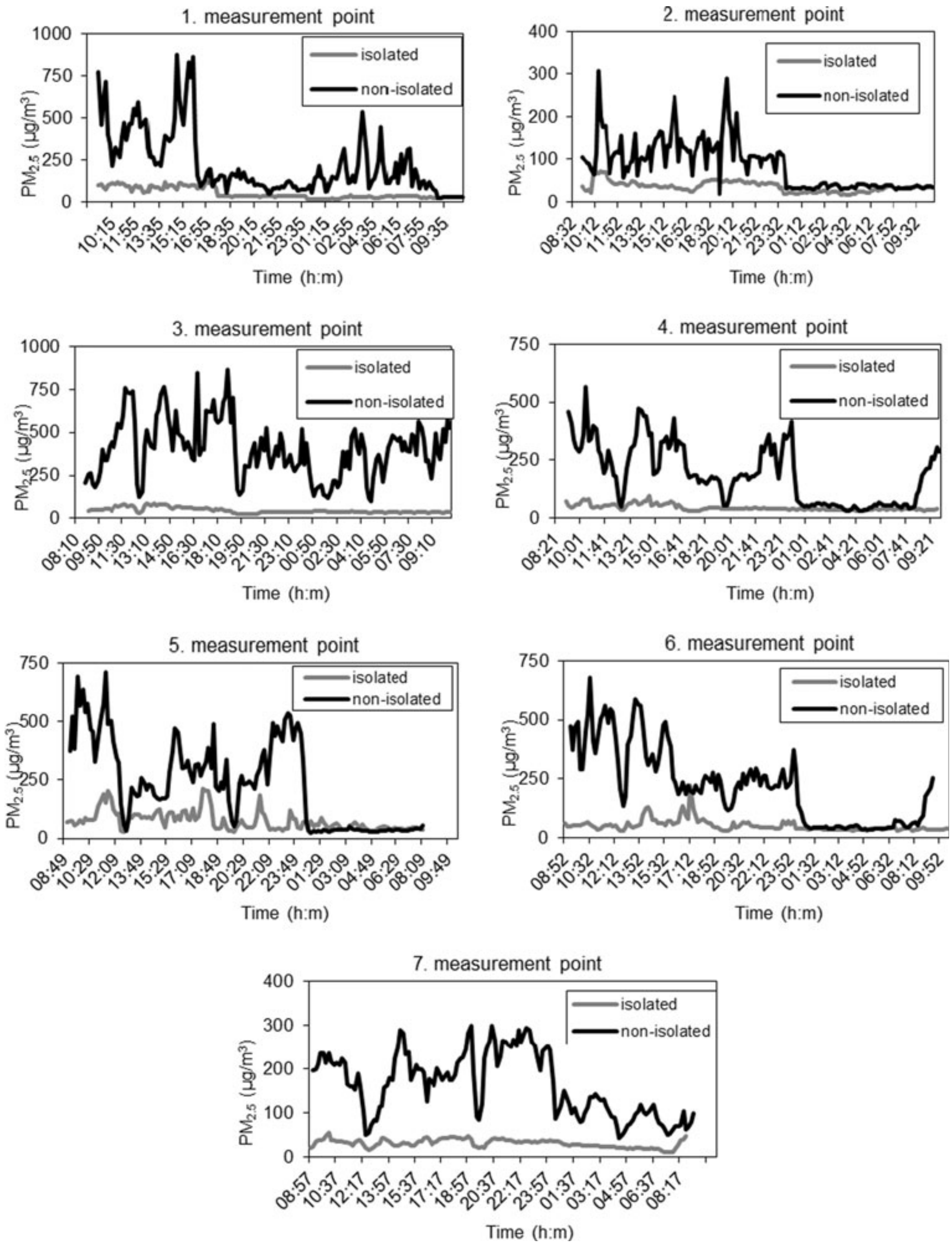

Fig. 2 $PM_{2.5}$ concentration in the seven measurement points of manufacture department for two conditions: (1) machines non-isolated, (2) machines isolated

Table 1 $PM_{2.5}$ concentrations ($\mu g/m^3$) in the manufacture department

Measurement points (MP)	Measurement conditions	
	Non-isolated machines	Isolated machines
1. MP	227.9 ± 189.0	52.2 ± 31.7
2. MP	86.3 ± 57.1	35.5 ± 12.4
3. MP	404.9 ± 164.9	45.7 ± 15.5
4. MP	188 ± 128.8	44.0 ± 12.5
5. MP	230.4 ± 185.0	74.4 ± 40.6
6. MP	220 ± 161.9	51.3 ± 24.7
7. MP	163.3 ± 71.9	31.0 ± 9.2

throughout the day. The different measurement days correlated at the level of 0.5–0.6 regarding the daily $PM_{2.5}$ concentration variation. This variation resulted from the regularity of the daily operations conducted during the manufacturing process. $PM_{2.5}$ concentration suddenly decreased when there was a lunch or dinner break (12:00/18:00), at the change of shifts, when wires were replaced in the machines (at an av. of 15 min) and when a component needed to be changed (at an av. of 1 h).

As can be seen in Table 1, average $PM_{2.5}$ concentration varied between 404.9 ± 164.9 $\mu g/m^3$ and 86.3 ± 57.1 $\mu g/m^3$ when the machines were not isolated. However, $PM_{2.5}$ concentrations showed homogeneous change between points and throughout the day and decreased between 74.4 ± 40.6 μg/m^3 and 31.0 ± 9.2 μg/m^3 when the machines were isolated. The statistical significance of the measurement point difference was determined by the Student's *t* test. As shown in Fig. 2 and Table 1, there was no statistically meaningful difference in $PM_{2.5}$ concentration at the different points with the isolated machines inside the facility ($p > 0.05$). However, machine isolation caused a decrease in $PM_{2.5}$ concentration level by 2.5 to 8.8 fold.

At the eighth point, which measured the outdoor air, $PM_{2.5}$ concentration during the working period over 3 days at the same measurement period was measured. Outdoor air $PM_{2.5}$ levels showed variation between 50 and 100 μg/m^3. The basic cause of the air pollution inside the facility is the operation of the machines used in the production processes.

There are two offices in the factory that are close to the manufacturing sector. The first office houses the administrative staff, and the second office, known as the quality office, ensures product quality control. $PM_{2.5}$ concentration measurements were obtained during the work day (09:00–17:00) over 3 days at both of the offices, and the average $PM_{2.5}$ concentration change is shown in Fig. 3. During the working hours at the second office, average $PM_{2.5}$ concentrations were measured at 68.5 μg/m^3; in the first office, the average $PM_{2.5}$ concentration was 62.8 μg/m^3. Until the afternoon, a similar change in $PM_{2.5}$ concentration at both of the offices was observed. In the afternoon, due to the analysis and controls of the products manufactured, the activity and $PM_{2.5}$ concentration increased in the second, quality control office.

As previously mentioned, CO, CO_2 and VOC recordings were obtained at seven measurement points in the manufacturing department of the factory. The measurements were conducted at every measurement point during the work day over 3 days when the manufacturing machines were isolated. The average CO, CO_2 and VOC concentration changes at seven different locations throughout the day are illustrated in Fig. 4. In addition, average CO, CO_2 and VOC concentration values, ambient temperature and humidity were evaluated and are summarized in Table 2.

The ambient temperature inside the facility generally ranged between 20 and 25°C during the measurement periods. Humidity values were measured between 40 % and 50 %. However, at the first measurement point, the average temperature reached 30°C and the lowest humidity value was obtained (Table 2). The higher temperature and lower humidity values at this measurement point are expected because this location is in the section where the heat treatment furnaces are located.

As can be seen in Table 2 and Fig. 4, average CO_2 concentration varied between 576.7 ± 18.7 and 642.6 ± 30.4 ppm. CO_2 concentrations showed homogeneous change throughout the day and between measurement points; there

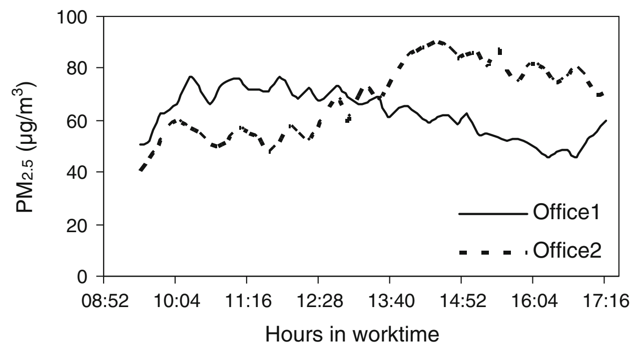

Fig. 3 $PM_{2.5}$ concentration in the first office and the second office at the work time in day

was no statistically significant difference between different measurement points ($p > 0.05$). CO concentrations were highest at the second and first measurement points (15.8 ± 3.0 and 11.1 ± 5.9 ppm, respectively). At the third, fourth and seventh measurement points, the average CO concentration was recorded as 7 ppm and no statistical difference was observed ($p > 0.05$) between these points. The fifth measurement point showed the lowest CO concentration with a value of 0.8 ± 0.6 ppm. VOC concentration changes were similar to CO concentration changes across measurement points. The highest VOC concentration (0.58 ± 0.90 ppm) was obtained at the second measurement point, whereas the lowest value (0.06 ± 0.07 ppm) was recorded at the fifth point.

At the measurement points, a significant correlation (R = 0.87) was found between VOC and CO concentrations. However, a moderate correlation (R = 0.56) between CO_2 and CO concentrations was obtained. The correlation between CO_2 and VOC concentrations was weaker (R = 0.39). This result suggests that VOC and CO emissions perhaps arose from similar resources at the measurement points. At the locations with the heat treatment furnaces higher CO and VOC concentrations were obtained. Clearly, VOC and CO emissions stemmed from combustion inside the facility.

Outdoor air CO_2 and VOC concentrations varied between 414 and 562 ppm and 0 and 1 ppm, respectively. There were no significant differences between outdoor and work environment CO_2 and VOC concentrations. However, outdoor CO concentrations (average 1.3 ppm) were lower than in the work atmosphere. The basic cause of CO pollution inside the facility is the operation related to the heat furnace processes.

The World Health Organization (WHO) states that the limit values specified for indoor air quality must be smaller than outdoor air limit values. The $PM_{2.5}$ concentrations showed compliance with the standards of the occupational Safety and Health Administration OSHA (5,000 μg/m^3) in terms of occupational health, whereas

Fig. 4 The CO_2, CO, and VOC concentrations in the seven measurement points (MP) of manufacture department

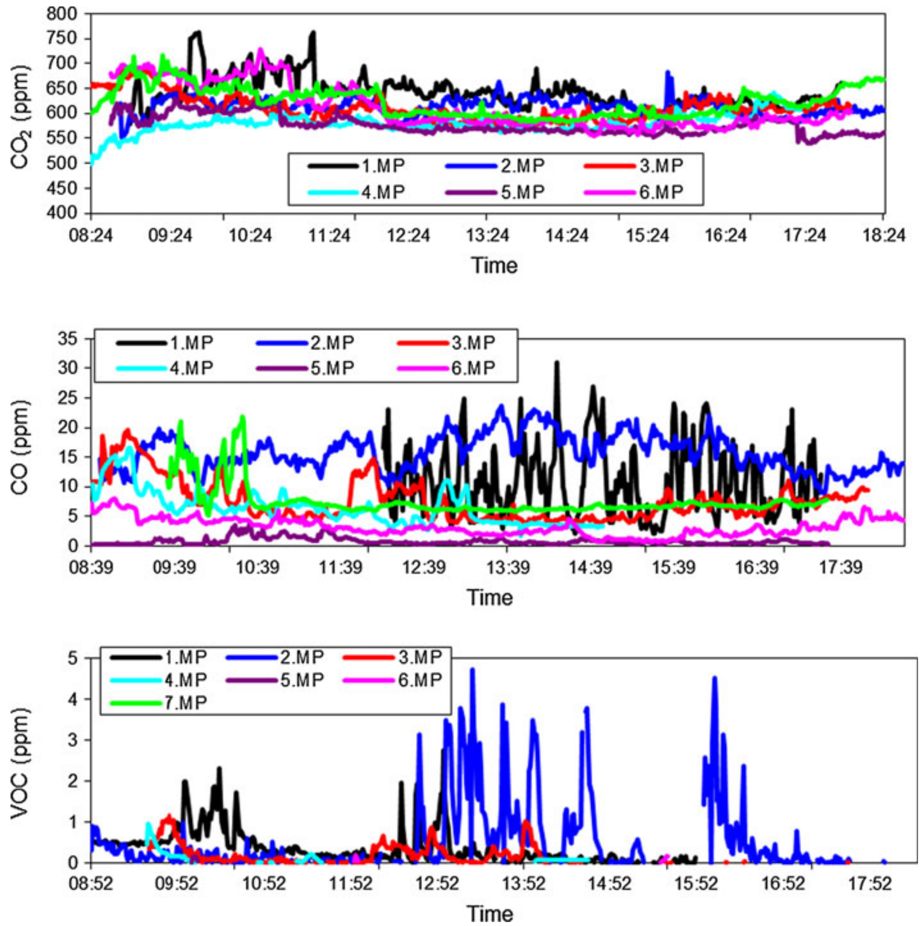

Table 2 CO, CO_2 and VOC concentrations (ppm) in the manufacture department

Measurement points (MP)	Measurement conditions				
	CO	CO_2	VOC	Temperature (°C)	Relative humidity (%)
1. MP	11.1 ± 5.9	642.6 ± 30.4	0.39 ± 0.41	30.5 ± 1.5	39.5 ± 4.5
2. MP	15.8 ± 3.0	612.8 ± 16.6	0.58 ± 0.90	23.3 ± 1.5	45.0 ± 2.0
3. MP	7.8 ± 3.4	612.2 ± 26.7	0.21 ± 0.26	23.9 ± 0.8	42.7 ± 3.0
4. MP	6.4 ± 2.9	578.8 ± 18.3	0.14 ± 0.17	21.3 ± 0.7	50.0 ± 1.2
5. MP	0.8 ± 0.6	576.7 ± 18.7	0.06 ± 0.07	21.9 ± 0.8	46.7 ± 2.2
6. MP	3.2 ± 1.5	612.5 ± 43.8	0.10 ± 0.06	20.8 ± 0.6	46.2 ± 2.3
7. MP	7.5 ± 2.7	623.4 ± 29.4	ND	18.5 ± 1.8	49.2 ± 2.5

ND not detected

they exceeded the standards (daily average 35 $\mu g/m^3$) specified by the WHO for public health. Inside the factory, the isolation system installed on the manufacturing machines showed a strong influence on $PM_{2.5}$ concentrations, effectively reducing the particulate matter. Therefore, isolation systems should be developed such that a central ventilation system can be used to improve the indoor air quality of any facility.

References

Brouwer DH, Gijsbers JHJ, Lurvink MWM (2004) Personal exposure to ultrafine particles in the workplace: exploring sampling techniques and strategies. Ann Occup Hyg 48(5):439–453

Demou E, Peter P, Hellweg S (2008) Exposure to manufactured nanostructured particles in an Industrial pilot plant. Ann Occup Hyg 52(8):695–706

Demou E, Mutamba G, Wyss F, Hellweg S (2009) Exposure to PM1 in a machine shop. Indoor Built Environ 18(6):514–523

Elihn K, Berg P (2009) Ultrafine particle characteristics in seven industrial plants. Ann Occup Hyg 53(5):475–484

Eninger RM, Rosenthal FS (2004) Heart rate variability and particulate exposure in vehicle maintenance workers: a pilot study. J Occup Environ Hyg 1:493–499

Evans DE, Heitbrink WA, Slavin TJ, Peters TM (2008) Ultrafine and respirable particles in an automotive grey iron foundry. Ann Occup Hyg 52(1):9–21

Evans DE, Ku BK, Birch ME, Dunn KH (2010) Aerosol monitoring during carbon nanofiber production: mobile direct-reading sampling. Ann Occup Hyg 54(5):514–531

Hsu Y, Wu CY, Lundgren A, Birky BK (2008) Size distribution, chemical composition and acidity of mist aerosols in fertilizer manufacturing facilities in Florida. Aerosol Sci 39:127–140

Iavicoli I, Laurini C, Carelli G (2005) Occupational exposure to low levels of organic and inorganic substances in a chemical plant for the production of terephtalic acid dimethyl ester. Microchem J 79:399–404

Kuo SC, Hsieh LY, Tsai CH, Tsai YI (2007) Characterization of $PM_{2.5}$ fugitive metal in the workplaces and the surrounding environment of a secondary aluminum smelter. Atmos Environ 41:6884–6900

Sivulka DJ, Conard BR, Hall GW, Vincent JH (2007) Species-specific inhalable exposures in the nickel industry: a new approach for deriving inhalation occupational exposure limits. Regul Toxicol Pharmacol 48:19–34

Vincent JH, Clement CF (2000) Ultrafine particles in workplace atmosphere. Philos Trans R Soc 358:2673–2682