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INDOOR AIR QUALITY OF A CAFETERIA WITH A ROTOR TURBINE VENTILATOR (RTV) AND CROSS-CORRELATIONS BETWEEN INDOOR AIR POLLUTANTS, OCCUPANCY RATE AND METEOROLOGICAL PARAMETERS

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Abstract

Indoor air quality (IAQ) improvement potential of rotor turbine ventilator (RTV) was researched by setting up an RTV on the outer part of the chimney of a kitchen, located in a "windy" city, Çanakkale, Turkey. Efficiency of RTV was assessed by preliminary tests, conducted in a three-storey restaurant. After obtaining positive results in terms of airborne bacteria count (TBC) from these tests, long-term measurements were carried out in a cafeteria by air sampling before and after setting up the RTV. In addition to airborne bacteria measurements, concentrations of Total Volatile Organic Compounds (TVOC), Carbon monoxide (CO), Carbon dioxide (CO_2), ozone and (fine and coarse) particulate matters (PM) were also measured before and after the RTV installation on the funnel of the cafeteria. Moreover, temperature and relative humidity were measured on-line, and the meteorological parameters were recorded. Furthermore, the number of people in the cafeteria during the air sampling was counted. After the RTV installation, levels of TBC, sum of PM, TVOC, and CO_2 clearly decreased, while levels of ozone and CO showed no significant variation during the study. Overall, RTV has potential to improve IAQ, when combined with natural ventilation.

In addition to examining the efficiency of RTV, cross-correlations were found among the air pollutants, meteorological/thermal comfort parameters, and the occupancy rate, regardless of the RTV installation. Moreover, statistically significant relationships (p<0.05) were found for number of people in the cafeteria and levels of both CO_2 and TBC throughout the entire study.

Key words: airborne bacteria, indoor air quality, rotor turbine ventilator

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1. Introduction

Ventilation has considerable effects on indoor air quality (IAQ) of any closed environment. Providing comfortable indoor air conditions in naturally ventilated spaces is still of issue especially in kitchen-type microenvironments and where occupancy rate is relatively high. Inadequate ventilation can result in excessive humidity, condensation, overheating, and accumulation of odours, smokes and pollutants (Khan et al., 2008). Although among the heating, ventilation and air-conditioning (HVAC) applications, using air cooling devices has been increasing during the last decade, natural ventilation through windows and openings is still too common in most parts of Turkey, particularly cities which have Mediterranean climate conditions. The rotary ventilator was first used by Meadow and patented in 1929 by the US Patent Office (Meadow, 1929). A rotary ventilator (i.e. roof-top rotor ventilator or, hereafter, rotor-turbine-ventilator, RTV) includes a rotor head provided with multiple driving helicoidal blades that withdraw the air from the associated end of the ventilator pipe, discharging it

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laterally from the ventilator (Khan et al., 2008; Meadow, 1929). RTVs are commercially available with different diameter, height, blade designs, and materials (Lien and Ahmed, 2011). Airflows through the RTV are proportional to the diameter/height of the RTV and the wind speed (Kuo and Lai, 2005; Lai, 2003; West, 2001). RTV systems are particularly common in windy cities due to the prevailing winds to rotate the turbine ventilator and have advantages such as ease and inexpensive costs of the installation. The height of the RTV systems can be as small as 23 cm (MC model) or as large as 75 cm (oversize model), according to the amount of air flow, passing along the chimney. It is found that the dimensions of the RTV are proportional to ventilation capacity of the RTV (Lai, 2003; West, 2001). It is believed that RTV systems have influences on improving the comfort level of the air in indoor environments, particularly in kitchens of cafeterias and restaurants. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) also suggest roof ventilation for the removal of moisture inside the buildings (ASHRAE, 1999). Kuo and Lai (2005) found a positive effect of roof turbine ventilator on bathroom ventilation. Types of hybrid roof ventilators (Ismail and Abdul Rahman, 2010) and the other roof ventilators were compared for appropriateness of tropical Malaysia conditions (Al-Obaidi et al., 2014a). Hybrid turbine ventilator was used to reduce the attic temperature and the humidity in Malaysia (Al-Obaidi et al., 2014b). However, few studies are available, examining the influence of RTV or similar roof-top ventilators on IAQ.

Recently, indoor air quality (IAQ) studies have focused on the most common indoor air pollutants, such as Volatile Organic Compounds (VOCs), particles (PM), bioaerosols, CO_2, CO, and ozone. Those pollutants are cause for high public concern due to their adverse health effects (Carrer et al., 2001; Douwes et al., 2003; Dockery et al., 1993; Fiegel et al., 2006; Smedje et al., 1997; Wieslander et al., 1997) and the fact that VOCs and ozone can trigger other reactions in the air. Also, since those pollutants are ubiquitous in most of the indoor environments (Colbeck et al., 2010; Cox et al., 2002; Morawska et al., 2003; Mentese et al., 2012a; Rehwagen et al., 2003), monitoring their levels is important. However, still there is a need to deal with those air pollutants all together, not only by monitoring the levels of each individual pollutant, but also searching for the associations among the indoor air pollutants, outdoor air pollution, meteorological factors, and other factors such as human behaviors.

Since there is a need to improve IAQ with inexpensive and easy-to-use methods, new studies should focus on techniques such as RTV applications. The main aim of this study was to search for the contribution of the RTV on IAQ (levels of airborne bacteria, Total Volatile Organic Compounds, particulate matter, CO_2, CO, and ozone) and thermal comfort parameters such as temperature and relative humidity. RTV was tested at a cafeteria in Canakkale, Turkey, where windy (wind speed $\geq$ 7 m s^{-1} at 50 m above the sea level and the average number of windy days that wind speed was between 10.8 and 17.2 m/s is about 180 days $year^{-1}$) and relatively warm meteorological conditions, showing a transient character of both the Mediterranean and Black Sea regional climatic conditions. Before testing the effect of RTV on IAQ, preliminary test was conducted in another restaurant in terms of observed bacteria levels before and after RTV installation. Also, included in the study were: searching for cross-correlations among the IAQ measurements, thermal comfort levels such as temperature and humidity, meteorological parameters and the number of people inside the cafeteria. A final goal of this study is to help increase public awareness of the need to provide a better IAQ in kitchen-based microenvironments.

2. Materials and methods

2.1. Preliminary tests

A RTV (see Fig. 1) was installed on the outer part of a funnel of a three-storey restaurant, located in Çanakkale, is one of the windiest cities of Turkey. The RTV used in this study is a curved vane passive turbine ventilator and commercially called as B-type RTV (height: 45 cm, width: 43 cm, and the bed width: 37 cm). Airborne bacteria samples were collected in September - October, 2012 from four different parts of the restaurant (two points in the ground floor-dining room, one in the kitchen, and one in the second floor-dining room), and from its terrace as an outdoor sample right before the installation of RTV. After the installation of RTV, airborne bacteria samples were collected at the same sampling points on 5 different days when the meteorological conditions such as wind speed and direction, cloudiness, temperature, and the humidity levels were similar based on weather forecasting data, which were obtained from Turkish Meteorological Institute.

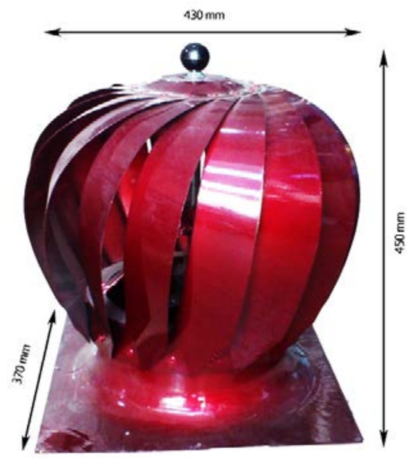

Fig. 1. Rotor Turbine Ventilator (RTV)

Airborne bacteria sampling and enumeration procedure was prescribed before Mentese et al. (2009). In brief, air samples were impacted onto sterile Plate Count Agar (PCA) (Salubris Co., Turkey) by a single-stage bioimpactor (SKC Inc.) at flow rate of 28.3 L/min. After the incubation period at 37 °C for 2 days, growth of bacteria colonies on the agar was counted under a light source. Total Bacteria Count (TBC) was calculated as colony forming unit per drawn air in m^3 (CFU/m^3). Since the sampling duration was set to 2 min, for the preliminary tests Limit of Detection (LOD) value for TBC was 18 CFU/m^3. Temperature and Relative Humidity (RH) were measured at the time of the sampling. Also, wind speed was measured online by an anemometer (Rotronic, Switzerland).

2.2. IAQ monitoring in the cafeteria

After getting positive outcomes from the preliminary tests, a RTV was tested in another location, a cafeteria, for longer monitoring duration. A RTV was installed on the outer part of the funnel of an open type kitchen cafeteria. The outer part of the funnel was about 10 m in height from the kitchen's hood. The inside view of the kitchen and the outside view of the chimney line, installed with the RTV were shown in Figs. 2 and 3, respectively. IAQ measurements were conducted in a university cafeteria, located on the ground floor (see Fig. 4 for the plan of cafeteria) during March – May, 2013. The main characteristics of the cafeteria are: the heating/cooking fuel was natural gas; traffic density on the main road was less; semi-urban area; variable number of occupants indoors; no plant indoors; moderate amount of pressed wood products' availabilities (wood products are accounting for approx. ½ of the room volume); no carpet covering, and naturally ventilated environment.

Fig. 2. An inside view of the kitchen of the cafeteria

Air quality measurements were conducted during daytime from 1.5 m height at the centre of the room for indoor air samples and at least 2 m away from the building for outdoor samples (ISO, 2004). Parallel indoor and outdoor samplings were conducted for each sampling day. The cafeteria is open from 8:30 am to 5:00 pm and one of the doors was kept open during the day.

Fig. 3. An outside view of the chimney line, installed with the RTV (Cafeteria study)

Air quality measurements were carried out at three different periods of a day: morning (M) period at 9:00 am, noon (N) period at 1:00 pm, and afternoon (A) period at 4:30 pm. Airborne bacteria samples were collected and counted in the same manner as the preliminary tests.

However, unlike the airborne bacteria sampling in the preliminary tests, the sampling duration was this time set to 5 min and thus the LOD value for the cafeteria study was 7 CFU/m^3. Levels of CO, CO_2, TVOC, temperature, and RH were measured by an on-line IAQ measurement instrument (Advancedsense IAQ meter, Graywolf, USA). Particle concentration was measured with a size-selected 6-channeled particle counter (Lighthouse, Graywolf, USA) from diameter of 0.3 microns to 10 microns. Similar to preliminary tests, wind speed at the ground level was measured online by the anemometer. Also, meteorological parameters that we did not measure (solar duration and rain amount) were also obtained from Turkish Meteorological Institute throughout the study, and the number of people in the cafeteria during the air sampling was counted.

2.3. Statistical analyses

All statistical analyses were performed using Statgraphics 3.0 software (free software).

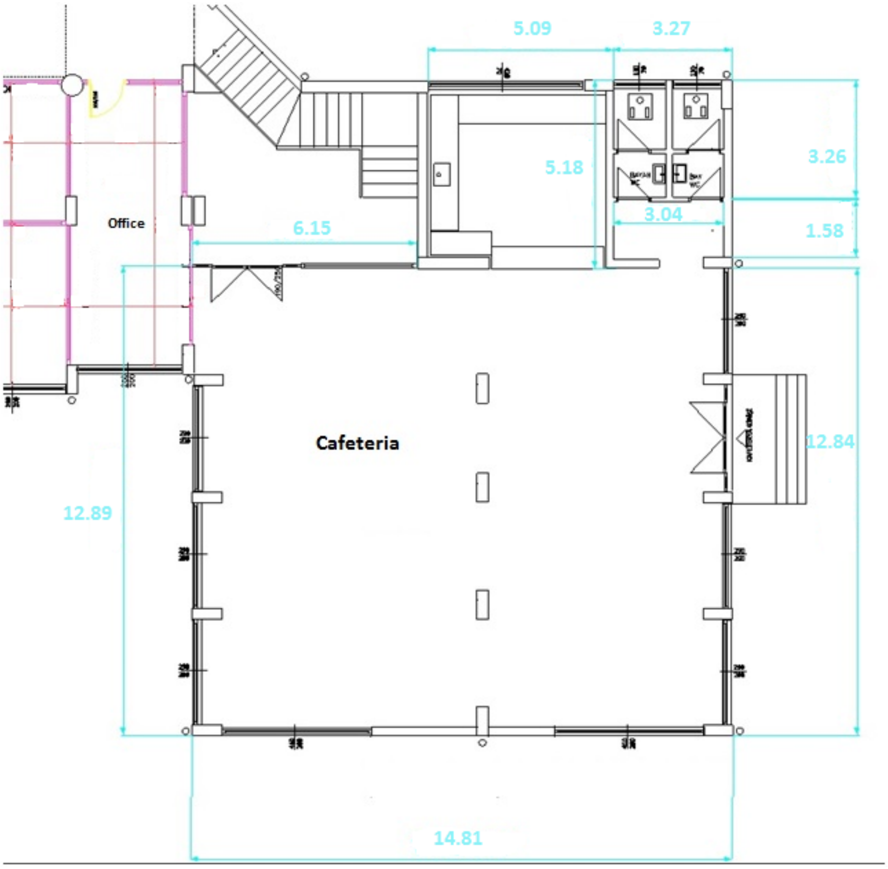

Fig. 4. Plan of the cafeteria (units in meter)

Concentrations of airborne bacteria, CO, CO_2, ozone, TVOC, and PM were assumed to be independent variables; while sampling period (before/after RTV installation and period of the day: morning-noon-afternoon) and sample type (indoor/outdoor) were assumed to be dependent variables for relating the factors affecting IAQ.

The data are generally presented as arithmetic mean values, median (med), 25th and 75th percentiles, standard deviation (sd), and range (minimum-maximum values). Several factors (temperature, RH, number of people, and meteorological parameters) were taken into account statistically. Statistically significant differences in air pollutant levels were searched by t-test and Kolmogorov-Smirnov test. Associations between the parameters were estimated statistically by linear regression model, analysis of variance (ANOVA) tests and Spearman rank correlation as well. Only variables for $p<0.05$ are accepted as statistically significant (Mentese et al., 2012a, 2012b).

3. Results and discussion

3.1. The results of the preliminary tests

During the preliminary tests, recorded meteorological conditions were, briefly, 29 °C, 58% RH, and average wind velocity at the RTV level was 5.5 m/s (see Table 1). Rain was not observed during the preliminary tests. Duplicate airborne bacteria samples were collected before and after the RTV installation onto the restaurant's chimney. Although the number of colonies observed on the PCA were almost similar to each sampling point, the average value of the duplicate bacteria concentrations was considered. A total of 10 airborne samples were collected at the sampling points of the restaurant right before the RTV installation onto the restaurant's chimney. After the RTV installation, airborne bacteria samplings were conducted on the relatively similar five days in the restaurant (n = 10). Decreases in levels of airborne bacteria at the sampling points are given in Fig. 5. Fig. 5 shows that TBC levels decreased at all the sampling sites with average decrease percentages from 48% (in the second floor dining room) to 98% (in the kitchen). Since the total number of the sampling days was not sufficient to ascertain the influence of the RTV on IAQ and IAQ should be considered not only by airborne bacteria level but also particles, gaseous pollutants and thermal comfort parameters such as temperature and RH, another longer experimental setup was therefore planned.

3.2. The effect of RTV on IAQ of the cafeteria

Results of IAQ measurements, conducted in the cafeteria and outdoors, were compared before and after the RTV installation. TVOC levels measured in the cafeteria before and after the RTV set up are shown in Fig. 6 which depicts a decrease in TVOC levels after the RTV installation for three periods of the sampling days.

TBC levels measured in the cafeteria before and after the RTV set up are shown in Fig. 7. According to Fig. 7, TBC levels decreased after the RTV setting up for noon and afternoon periods of the sampling days.

Table 1. Meteorological parameters during the preliminary tests

Parameter	***Arithmetic mean ± sd***
Temperature (°C)	29.1 ±0.7
Relative humidity (%)	58.1 ±7.1
Wind speed (m/s)	5.5 ±0.8
Prevailing winds	NE - NNE
Rain amount (mm)	0

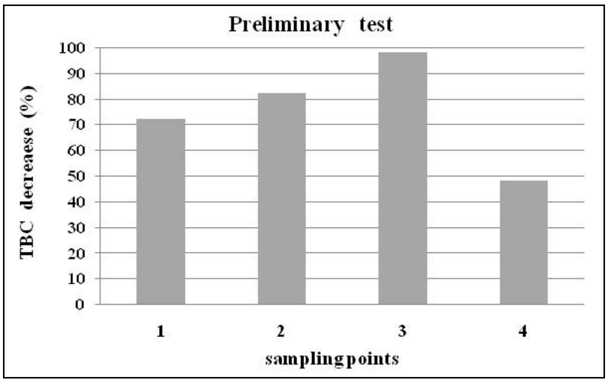

Fig. 5. TBC decrease percentages (%) at the sampling points: 1: ground floor dining room-near the entrance, 2: ground floor dining room-far from the entrance, 3: kitchen, 4: second floor dining room

During the morning period, mean and median values of TBC levels were found to be slightly higher after the RTV setting up than before the RTV installation. Since the cafeteria was closed from afternoon to morning, environmental conditions might have not enabled any dilution of indoor air other than accumulation of some of the pollutants such as airborne bacteria. Furthermore, bacteria levels were observed to be close during all 3 periods before the RTV installation (approx. 500 CFU/m^3 on average). The door of the cafeteria was kept open both before and after the RTV installation. If door opening had an important effect on bacteria levels in the cafeteria, clear decreases in bacteria levels would be expected throughout the noon and afternoon periods before the RTV installation. Since this decreasing trend was not seen, we concluded that opening of the door of the cafeteria had no marked effect on bacteria levels.

CO_2 levels measured in the cafeteria before and after the RTV setting up were shown in Fig. 8. This figure shows the decrease in CO_2 levels after the RTV setting up for noon and afternoon periods of the sampling days. During the morning period, mean and median values of CO_2 levels were found to be close to those from before and after the RTV setting up, as well as similar to TBC levels observed in the morning.

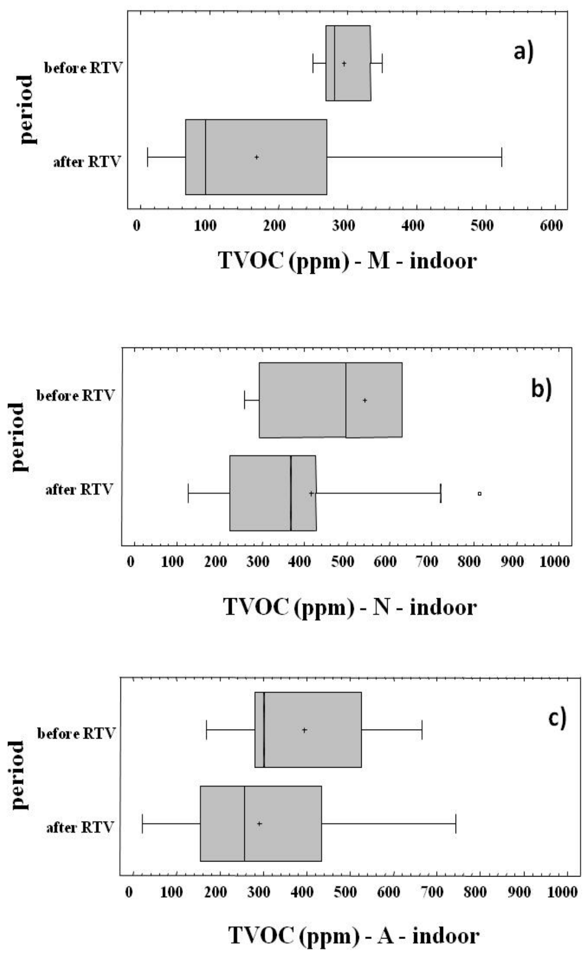

Fig. 6. TVOC levels (ppm) inside the cafeteria before and after the RTV setting up a) morning, b) noon, and c) afternoon periods (hereafter boxes show 25th-75th percentiles, lower and upper bars show the non-outlier ranges, lines inside the boxes show the median values, symbols of '+' inside the boxes represent the mean values, and '□' designate the outliers)

The CO_2 levels measured during the morning are representing "normal levels" (600 ppm is assumed to be normal levels when natural CO_2 levels of ambient air was considered as 350 ppm), indicating that there were no significant CO_2 source (e.g. occupancy) in addition to normal indoor air composition during the morning period. Probably due to this reason, CO_2 levels measured before and after the RTV installation were similar to each other during the morning periods.

Clear effects of the RTV installation on CO_2 levels were observed during noon and afternoon periods when the the human occupany was occured. No clear concentration variations were observed for either ozone or CO depending on the RTV setting up. Also, measured levels of ozone or CO were relatively low (<1 ppm) to make a comparison. Thus, their results were not given hereafter.

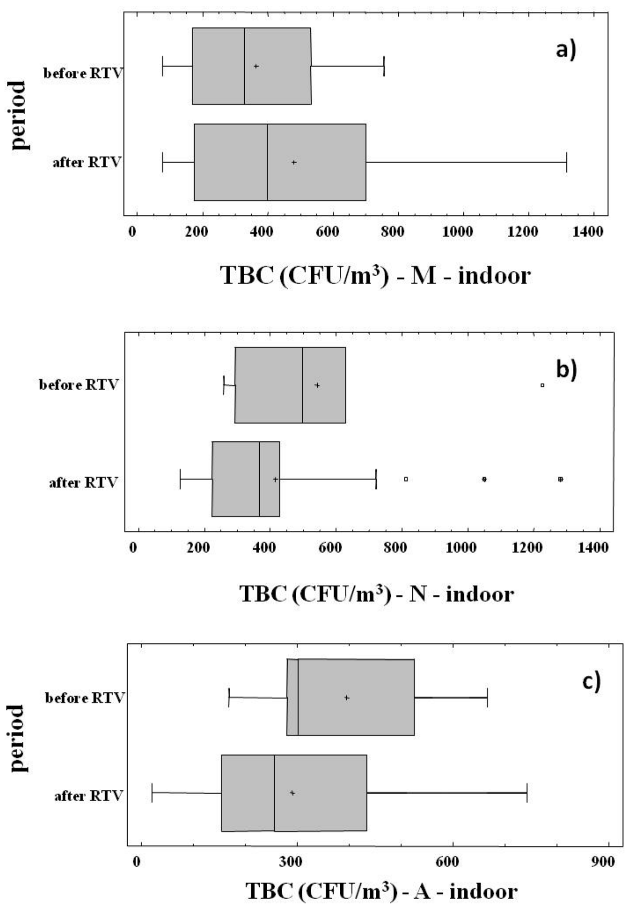

Fig. 7. TBC levels (CFU/m^3) inside the cafeteria before and after the RTV setting up a) morning, b) noon, and c) afternoon periods

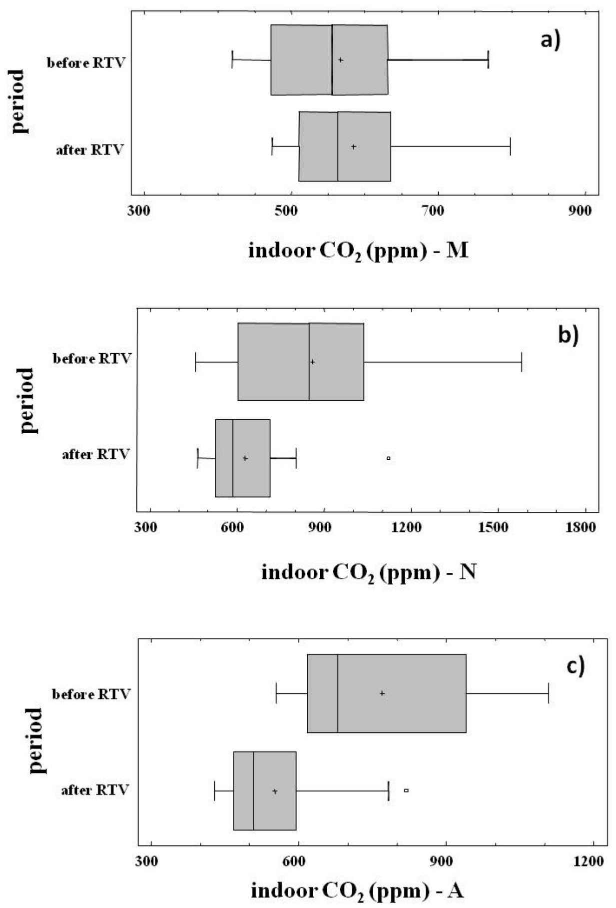

Fig. 8. CO_2 levels (ppm) inside the cafeteria before and after the RTV setting up a) morning, b) noon, and c) afternoon periods

3.3. Cross-Correlations among the levels of air pollutants, meteorological parameters and occupancy rate in the cafeteria

Regardless of the RTV setting up time, all measurements carried out within this study were examined to figure out the general IAQ of the cafeteria by correlating the all measured indoor air parameters. Meteorological parameters (wind speed and direction, solar duration, and rain amount) during the cafeteria campaign for each sampling time are provided in Table 2. As a summary, the outdoor temperature was warm, not humid, and wind speed was moderate-strong during the study. Since one of the doors of the cafeteria was always kept open during the day, strong associations were found between indoor and outdoor temperature/RH values (correlation coefficient of r>0.8 and p>0.05). The potential influence of these meteorological factors on measured levels of indoor air pollutants are assessed by linear regression tests (Table 3). According to Table 3, positive associations were found between RH and indoor air pollutants, while negative associations were found between temperature and indoor air pollutants. In general, people were eating inside the cafeteria when the weather was warmer inside of the cafeteria than outside, which can result in accumulation of the indoor air pollutants in the cafeteria. Solar duration had a negative effect on CO_2 levels in the afternoons. The other meteorological factors (rain amount, wind speed and direction) showed no statistically significant associations among the levels of indoor air pollutants (p>0.05).

Table 2. Meteorological Parameters during the Cafeteria Study

Parameter	***Arithmetic mean (min - max)***
Temperature (°C)	21.1 (11.3 - 31.6)
Relative humidity (%)	47.7 (21.3 - 64.5)
Solar duration (hour) [a]	14.7 (0 - 24)
Wind speed (m/s)	3.6 (1.4 - 9.7)
Prevailing winds	NE - SW
Rain amount (mm) [a]	0.3 (0 - 12)

[a] Solar duration and rain amount data was gathered from Turkish Meteorological Institute

Comparison of levels of air pollutants observed in indoor environments and their outdoors counterparts can be a useful tool in indicating whether there is a proliferation site indoors (Mentese et al., 2009; 2012a,b). Since parallel indoor and outdoor air quality measurements were carried out during the cafeteria study, relationships between indoor air quality and outdoor air quality were also studied. Statistically significant relationships were found between the indoor and outdoor levels of TVOC (r>0.50 and p<0.5), total PM (r>0.55 and p<0.001) and $PM_{0.3}$ (r>0.65 and p<0.0001), whereas no statistically significant relationships were found between indoor and outdoor levels of TBC and CO_2 (p>0.05).

Table 3. Correlations between Meteorological Parameters and IAQ Measurements

Factor	***Variable***	***r***	***p value***
Temperature	$PM_{0.3}$/total PM	-0.66	0.0003
	TBC	-0.69	0.0001
	TVOC	-0.63	0.0012
	CO_2	-0.65	0.0004
RH	total PM	0.52	0.0025
	TBC	0.64	0.0001
	CO_2	0.50	0.0039
Solar amount	[a]CO_2	-0.54	0.0017

[a] *correlation was found only in the afternoons*

Thus, sources of VOC and PM may originate from indoors and outdoors. Since no correlation was found among indoor and outdoor levels of TBC and CO_2, it can be concluded that major sources of indoor bacteria and CO_2 might be any source or activity done in cafeteria. As specified above, indoor bacteria levels were not found to be correlated with outdoor bacteria values, supporting previous studies which indicate that the most important influence of indoor bacteria levels is occupancy (Bonetta et al., 2010; Mentese et al., 2009; Pastuszka et al., 2000; Reponen et al., 1989).

In addition to linear regression results calculated for all data gathered from this study, Spearman rank correlations were also calculated to find out the statistically significant associations (Related pairs with Spearman correlation coefficient of r>0.4 and p<0.05 are only mentioned here) among the air pollutants, meteorological parameters, and the number of people in the cafeteria on the basis of three sampling periods. As can be seen from Table 4, statistically significant relationships were found for $PM_{0.3}$ - total PM, TBC - CO_2, TVOC - temperature (negative), total PM - CO_2, CO_2 - number of people, TBC – number of people, and $PM_{0.3}$ - CO_2 during three periods of the day. Statistically significant relationships were found for two periods of the day for other parameter pairs.

As previously stated, since the main sources of TBC and CO_2 seemed to be the occupancy, correlations found between these two parameters were expected. As the total count of $PM_{0.3}$ was found to be the major size among the diameters from 0.3 micron to 10 microns, a strong correlation exists between $PM_{0.3}$ and total PM found. In another study, size distribution of particles in indoor air was found to be dominated by finer particles (<1 micron) (Mentese, 2009). The influence of the number of people inside the cafeteria was also assessed for the measured air pollutants. As can be seen from Figs. 9 and 10, when the occupancy rate was categorized, effects of occupancy rate on levels of TBC and CO_2 were clearly seen for three periods of the day.

Table 4. Spearman Rank Correlations among the levels of indoor air pollutants, thermal comfort parameters (temperature and RH), and occupancy rate

Morning								
Variable	***CO_2***	***# of people***	***total PM***	***RH***	***temperature***	***$PM_{0.3}$***	***TBC***	***TVOC***
CO_2	1							
# of people	0.66[b]	1						
total PM	0.48[c]	0.05	1					
RH	0.03	0.06	0.22	1				
temperature	-0.16	0.07	-0,10	-0.20	1			
$PM_{0.3}$	0.45[c]	0.02	0.99[a]	0.24	-0.11	1		
TBC	0.70[b]	0.49[c]	0.41	0.13	-0.17	0.37	1	
TVOC	-0.34	0.25	0.01[c]	0.20	-0.79[a]	-0.01	0.20	1
Noon								
CO_2	1							
# of people	0.75[a]	1						
total PM	0.50[c]	0.09	1					
RH	0.51[c]	0.50[c]	0.28	1				
temperature	-0.53[c]	-0.48[c]	-0.21	-0.65[b]	1			
$PM_{0.3}$	0.45[c]	0.06	1.0[a]	0.28	-0.18	1		
TBC	0.86[a]	0.49[c]	0.64[b]	0.51[c]	-0.51[a]	0.61[b]	1	
TVOC	0.58[b]	0.33	0.43	0.32	-0.61[b]	0.40	0.69[b]	1
Afternoon								
CO_2	1							
# of people	0.42[c]	1						
total PM	0.55[c]	0.07	1					
RH	0.62[b]	0.38	0.44[c]	1				
temperature	-0.37	-0.08	-0.19	-0.57[b]	1			
$PM_{0.3}$	0.53[c]	0.08	1.0[a]	0.45[c]	-0.21	1		
TBC	0.59[b]	0.41[c]	0.32	0.64[b]	-0.58[b]	0.32	1	
TVOC	0.52[c]	-0.10	0.05	0.30	-0.53[c]	0.06	0.58[b]	1

[a] *p<0.001;* [b] *p<0.01;* [c] *p<0.05*

As the number of people inside the cafeteria decreased, levels of TBC and CO_2 decreased. Since it is known that the major sources of both TBC and CO_2 is the occupancy (Mentese et al., 2009, 2012a, b; Qian et al., 2012), observed results in this study supported this conclusion.

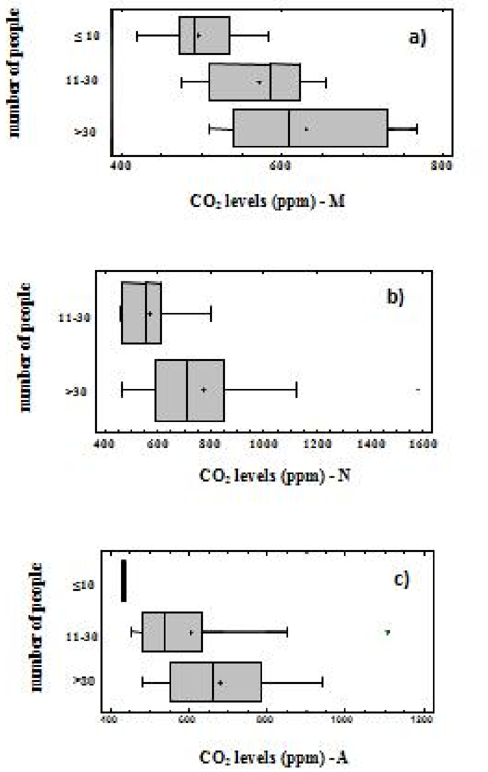

Fig. 9. Variation of TBC levels (CFU/m^3) vs. the number of people inside the cafeteria a) morning, b) noon, and c) afternoon periods

4. Conclusions

This study showed that RTV applications have the potential to improve IAQ. The RTV systems can be applied as a practical roof-ventilator in relatively windy and warm regions, similar to this study area, in addition to natural ventilation in order to provide better IAQ in terms of airborne bacteria, CO_2, VOC, and particles.

In addition to searching for the efficiency of RTV, cross-correlations were found among the air pollutants, meteorological/thermal comfort parameters, and the occupancy rate, regardless of RTV installation. Moreover, statistically significant relationships (p<0.05) were found for number of people in the cafeteria and levels of both CO_2 and TBC throughout the entire study.

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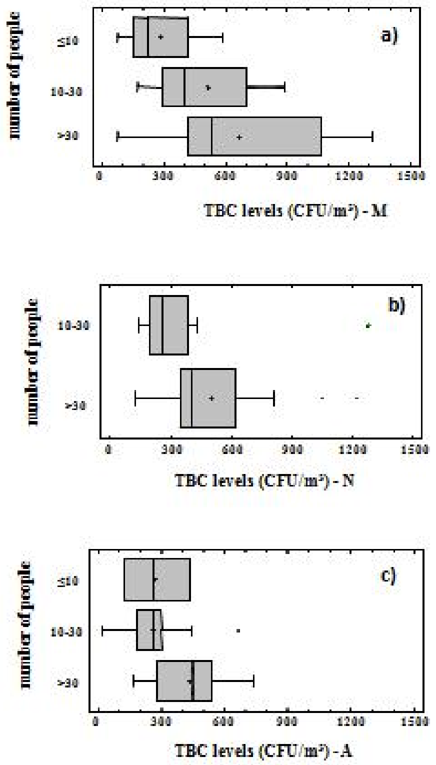

Fig. 10. Variation of CO_2 levels (ppm) vs. the number of people inside the cafeteria a) morning, b) noon, and c) afternoon periods

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