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AN EXPERIMENTAL STUDY OF THE INDOOR AIR QUALITY IN AREAS OF DIFFERENT USE

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ABSTRACT

The purpose of the present work was to study experimentally the indoor air quality status regarding PM_{10}, $PM_{2.5}$, TVOCs, CO_2, NO_x, SO_2 and O_3 in selected differently used areas. A flat on the third floor of a multi-storey building, located at a suburban area north-east of the centre of Athens and close to a heavily trafficked road and two offices of the Environmental Physics Department building at the University campus, in a suburban area were selected for the purpose of the measurements. The experimental campaigns covered several days in each area in order to include different indoor conditions and outdoor concentration levels. Total VOCs and CO_2 were measured on a continuous basis at selected locations only in the indoor environment with two sets of portable samplers. Indoor and outdoor NO_x, SO_2 and O_3 were measured with analysers. PM_{10} and $PM_{2.5}$ 24 hour averaged measurements were taken with the aid of two sets of indoor particle samplers.

Experimental results obtained from Offices 1 and 2 indicate that the indoor air quality in both offices is satisfactory with respect to NO_x, SO_2 and O_3. PM_{10} concentrations are well above the specified limits on days of smoking or closure of windows in both offices. The indoor air quality in Office 1 seems satisfactory with respect to CO_2 and total VOCs concentrations measured, even on days when smoking was taking place and windows were kept closed while all occupants were present. In Office 2, both CO_2 and total VOCs concentrations are elevated, even on days when the windows were open or smoking was not taking place, but do not exceed the specified limits, indicating poor air renewal.

Experimental data obtained from the residence indicate firstly that NO_x, SO_2 and O_3 concentrations in the indoor environment depend directly on the outdoor levels as they presented the same diurnal variation, while the indoor values were lower than the outdoor ones. Surprisingly enough, the total VOCs concentrations in the living room presented high values when windows were kept open indicating strong presence of outdoor sources. Furthermore, activities such as cooking, cleaning, smoking and use of indoor air fresheners further increased the total VOCs levels. Regarding CO_2 concentrations, they were almost constant indicating acceptable but not satisfactory renewal of the indoor air. Finally, PM_{10} concentration measurements were most of the time below the specified limits, with some exceptions mainly related to window opening and cooking

KEYWORDS: indoor air quality measurements, indoor sources, Total VOCs, PM.

1. INTRODUCTION

In the last decades, the air quality of indoor areas became of primary importance because of its effect on human health. The closure of natural openings of buildings for energy saving

purposes, the use of untested new materials as well as the poor air exchange affect drastically the indoor air quality. A result of this interference is the increase of many pollutant concentrations indoors, such as CO, CO_2, PM_{10}, $PM_{2.5}$ and total VOCs. Researchers have focused on the measurement of pollutants' concentrations in residences, offices, shopping malls and restaurants where people spend most of their everyday time, in order to compare the different indoor environments and identify pollution sources (Junker *et al.*, 2000; Lee *et al.*, 1999; Wargocki *et al.*, 2004; Synnefa *et al.*, 2003). A great portion of particulates originates from the outdoor air and enters the indoor environment via the ventilation systems, physical openings and cracks, while tobacco smoking, bad cleaning habits, resuspension and poor maintenance of the ventilation system filters lead to even higher levels. It should be mentioned that emissions from aged materials typically account for up to 30% of the total VOCs, while those generated from activities, office equipment, building maintenance and cleaning products account for the majority of VOCs. Furthermore, several studies have shown that the indoor air quality depends on the location of the buildings, the ventilation characteristics and the sources of air pollution, which exist at the area, while it was demonstrated that indoor air pollution levels can often exceed the outdoor levels (Assimakopoulos and Helmis, 2004; Jones *et al.*, 2000; Edwards *et al.*, 2001; Halios *et al.*, 2005).

Within that frame, the purpose of the present work was to study experimentally the indoor air quality status regarding PM_{10}, $PM_{2.5}$, TVOCs, CO_2, NOx, SO_2 and O_3 in selected differently used areas, a residence and two offices, for comparison purposes. The experimental campaigns covered several days in each area in order to include different indoor conditions and outdoor concentration levels. All measurements were taken during the winter period.

2. EXPERIMENTAL SITE AND INSTRUMENTATION

The two offices (Office 1 and 2) are located on the first floor of the Environmental Physics Department building at the University campus, which is in a suburban area not close to heavy traffic roads. In Offices 1 and 2, which are adjacent, 7 and 3 people work respectively. They are both equipped with electronic computers, printers and furniture, while only in office 1 a wall to wall carpet is installed. Office 1 covers an area of 70 m^2 and office 2, 20 m^2. It must be noted that smoking is permitted in Office 2. Measurements were taken in both offices simultaneously under different scenarios including occupation conditions, opening of windows, operation of the air conditioning system and smoking. Total VOCs and CO_2 were measured in both offices simultaneously, on a continuous basis at selected positions only in the indoor environment. Indoor and outdoor NOx, SO_2 and O_3 concentrations were measured at fifteen minute intervals in each office with the aid of an indoor-outdoor alternating valve. PM_{10} and $PM_{2.5}$ 24 hour averaged concentrations were measured in both offices. The experimental campaign was divided in two cycles, during the first cycle (16/12/2005 - 18/12/2005) all pollutants were monitored on a continuous basis while both offices were used as always. In the second cycle (19/12/2005 - 13/1/2006), different ventilation and occupation scenarios were applied every three hours, including operation of the A/C unit, opening of doors and windows (see Table 1).

The residence is a flat on the third floor of a 25 year old multi-storey building, covers an area of 140 m^2 and is occupied by 4 persons. It is located at a suburban area north-east of the centre of Athens and 300m away from a heavily trafficked road. Measurements were taken both in the kitchen, living room and immediate outdoor area (balcony), while everyday activities such as cooking, smoking, window opening, fireplace use and cleaning were performed. The residence walls were painted 2 months before commencing the experimental campaign and moreover, in the immediate outdoor area a number of pine trees were present, a source of biogenic VOCs. More specifically, 24 hour averaged PM_{10} and $PM_{2.5}$ and continuous total VOCs and CO_2 measurements were taken both in the kitchen and living room areas. NOx, SO_2 and O_3 were measured both in the living room and outdoor area (balcony) on fifteen minute intervals. The experimental campaign in the residence took place from 4/2/2006 until 19/2/2006. From 4 to 10/2/2006 all pollutants were monitored while the occupants performed their daily routines, while from 11 to 19/2/2006 several ventilation and

occupation scenarios were applied. It must be noted that a log book of activities was kept for all indoor areas monitored (see Table 2).

Table 1. Description of office use scenarios

Scenario	Explanation
A	windows open 10cm in 2 and 20cm in 1,door closed, A/C OFF
B	windows open 20cm in 2 and 30 cm in1, door closed, A/C OFF
C	windows open10 cm, door open, A/C OFF
D	A/C ON
E	All closed
F	windows open 10 cm, A/C ON
A**	windows open 10cm in 2 και 20cm in 1, door closed, A/C OFF
B**	A/C ON, all closed
C**	all closed

Table 2. Description of home use scenarios

DATE	SCENARIO
11/2/2006	Living Room: Smoking Kitchen: Cleaning and cooking with open windows and air suction
12/2/2006	Living Room: Cleaning Kitchen: Cooking with windows closed and air suction on
13/2/2006	Living Room: Fireplace use Kitchen: Cooking with window open
14/2/2006	Living Room: All windows closed Kitchen: all closed
15/2/2006	Living Room: Open window and fireplace use Kitchen: Cooking with window open
16/2/2006	Living Room: Window open Kitchen: Cooking, all closed
17/2/2006	Living Room: Fireplace use and smoking Kitchen: No activities
18/2/2006	Living Room: Cleaning and open window Kitchen: Cooking with open window and air suction
19/2/2006	Living Room: Smoking, fireplace use and open window Kitchen: no activities

The experimental instrumentation consisted of the following:

- Portable instrumentation – Two indoor air quality monitors (IAQRAE and ppbRAE of RAE systems) for TVOCs measurements (resolution: 10ppb and 1ppb respectively, accuracy: 10%) and one monitor (IAQRAE of RAE systems) for CO_2 measurements.
- Automated Horiba analyzers measuring NO, NO_2, SO_2 and O_3 interfaced to a data logger. The lowest detection limits (LDL) were 0.98, 0.61, 1.31 and 1 μg m^{-3}, respectively. The analysers were connected to an electronic alternating valve changing at fifteen minute intervals sampling between indoor and outdoor.
- Particle samplers measuring PM_{10} and $PM_{2.5}$, giving 24h mean concentrations calculated gravimetrically (weighing instrument KERN 770, accuracy 0.01mg) (Model 200 Personal Environmental Monitors (PEMTM) and SKC Universal DELUXE sampling air pumps of 2 L min^{-1}).

3. DISCUSSION OF EXPERIMENTAL RESULTS

3.1 Offices 1 and 2

Regarding the first experimental cycle in Office 1, (not shown here), the indoor air quality was satisfactory. Total VOC's concentrations did not exceed 31.3 μg m^{-3} when the room was fully occupied and 13.9 μg m^{-3} when the room was empty. These results compare well with the recommended limit of 300 μg m^{-3} for the indoor environment set by the international bibliography (Molhave, 1995; Seifert, 1990) as well as the Building Standard of 500 μg m^{-3}, which is in force in the State of Washington. The classical pollutants SO_2, NO_2 and NO presented very low concentrations 4, 6.2 and 15.2 μg m^{-3} respectively, during working days and 0.5, 3.4 and 5.9 μg m^{-3} respectively, when the room was empty. Interestingly enough, O_3 levels presented an increase from 30 μg m^{-3}, working days, to 43 μg m^{-3} (empty room), even though both values were low. The 24 hour averaged PM_{10} and $PM_{2.5}$ concentrations ranged at acceptable levels 48-55 μg/m^{-3} and 35 μg m^{-3}, respectively. The indoor air quality of Office 2, where smoking was allowed did not present significant differences in pollutants' levels, with the exception of total VOC's, which reached 74 μg m^{-3}. Furthermore, in this case both CO and CO_2 measurements were taken indicating acceptable conditions, 0.16 mg m^{-3} for CO and 1460 mg m^{-3} for CO_2 while the limit set by the American Society of Heating, Refrigerating and Air Conditioning Engineers for indoor spaces characterises satisfactory air quality CO_2 concentrations lower than 1000 ppm or 1800 mg m^{-3} (ASHRAE, 2003).

During the second experimental cycle it was observed that the highest total VOC's concentrations in Office 1 appeared when the A/C unit was operating and all doors and windows were closed (160 μg m^{-3} at 19/12/05) indicating high recirculation rate. Furthermore, when smoking was allowed (13/1/2006) the total VOC's levels did not exceed the specified limit values reaching 205 μg m^{-3} even though for the biggest part of the day all windows and doors were kept closed. The concentrations were even lower the rest of the experimental period ranging at 55 μg m^{-3}. CO_2 and classical pollutant (not shown here) concentrations remained at similar levels with the previous cycle indicating acceptable indoor conditions. On the other hand PM_{10} and $PM_{2.5}$ concentrations presented significant increase reaching 358 and 136 μg m^{-3} (Office 1, 4/1/06) and 337 and 177 μg m^{-3} (Office 1, 13/1/06) respectively, when smoking was allowed and indoor conditions were controlled (see Table 3). Similar behaviour was found in Office 2 regarding all pollutants measured. However, total VOCs levels were higher, reaching 306 μg m^{-3} and CO_2 was elevated, not exceeding the 1800 mg m^{-3} limit however, which may be attributed to its smaller size compared to the number of occupants (Table 3). Moreover, the particles concentrations were also similar compared to Office 1. Finally, in both offices CO levels were not elevated.

3.2 Residential apartment

Regarding the classical pollutants' levels, it is observed that indoor concentrations depend on the outdoor values but are in general lower. It is interesting to note that SO_2 concentrations reached unusually high values, of the order of 120 μg m^{-3}, in the outdoor environment during most experimental days, with a subsequent increase in the indoor levels, which may be attributed to the operation of central heating in the close vicinity of the residence. It is worth mentioning at this point that within the residential area the flat is located, there exist buildings with different heights all of which use central heating as it was winter time. High indoor and outdoor concentrations were found regarding NO, NO_2, O_3 originating from the outdoor environment, since as seen from Table 4 they are constantly higher. These high values were in a way expected since the residence is close to a heavy trafficked road.

Indoor TVOCs concentrations presented significant fluctuations ranging from 200 μg m^{-3} to 10000 μg m^{-3} depending on the type of activity that took place. More specifically, besides certain exceptions, a morning peak during working days appeared around 7 and 8 o'clock when the residents opened the living room window or used hair spray and total VOCs levels exceeded 1000 μg m^{-3} reaching even 8000 μg m^{-3}. High concentrations, of the order of 2000 μg m^{-3} appeared while cooking and 5500 μg m^{-3} while frying, especially when the kitchen window was closed. Smoking in the living room was also accompanied by high total VOCs levels. Finally, cleaning the living room with certain products (wood polisher, liquid and spray cleaner) resulted in high measured concentrations, of the order of 4000 μg m^{-3} which characteristically increased and decreased rapidly. CO_2 concentrations ranged between 700

and 1800 mg m^{-3} during all experimental days, not presenting a specific daily pattern and peaked to 3000 mg m^{-3} after smoking events. Total VOCs in the kitchen presented high values while cooking and showed an increase in concentrations at night when no activity was taking place, which could be attributed to re-emission of pollutants after deposition on the kitchen walls.

Table 3. Measured pollutants' levels in Offices 1 and 2

		Office 1							Office 2						
Date	Hour (LST)	CO (mg/m^3)	TVOCs ($\mu g/m^3$)	CO_2 (mg/m^3)	TVOCs ($\mu g/m^3$)	$PM_{2,5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	Scenario	CO (mg/m^3)	TVOCs ($\mu g/m^3$)	CO_2 (mg/m^3)	TVOCs ($\mu g/m^3$)	$PM_{2,5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	Scenario
19/12/2005	9:00-12:00				161			D	0.13	82	1734				D
	12:00-15:00				87			C	0.24	57	1679				C
	15:00-18:00				38			B	0.20	30	1453				B
	DAILY avg				50	22	47		0.2	30	1539		62	231	
	DAILY max				121				1	196	2113				
	DAILY min				2				0.01	6	1206				
20/12/2005	9:00-12:00				43			F		85	1730				F
	12:00-15:00				59			A	0.01	160	1784				A
	15:00-18:00				69			E	0.5	306	1707				E
	DAILY avg				35	26	50		0.09	92	1601		97	255	
	DAILY max				100				2	713	2310				
	DAILY min				2				0.01	7	1206				
3/1/2006	9:00-12:00							C**							C**
	12:00-15:00							A**			710.03				A**
	15:00-18:00							B**	0.33	81	690				B**
	DAILY avg					70	140		0.1	24	632		175	297	
	DAILY max								2	204	1150				
	DAILY min								0.01	7	305				
4/1/2006	9:00-12:00	0.09	77	921				C**				36			C**
	12:00-15:00	0.12	101	915				A**				17			A**
	15:00-18:00	0.28	132	1040				B**							B**
	DAILY avg	0.13	55	861		137	358					27	69	120	
	DAILY max	2	221	1320											
	DAILY min	0.01	3	442											
5/1/2006	9:00-12:00				45			C**	0.8	149	838				C**
	12:00-15:00				46			A**	1	181	850				A**
	15:00-18:00				43			B**	1	247	705				B**
	DAILY avg				38	35	53		1	81	730		88		
	DAILY max				107				3	801	2247				
	DAILY min				5				0.22	0.25	1277				
12/1/2006	9:00-12:00				15			C**	0.8	6	941				C**
	12:00-15:00				18			A**	1	83	1019				A**
	15:00-18:00				133			B**	2	286	1014				B**
	DAILY avg				56	35	71		1	125	991		195	337	
	DAILY max				97				2	949	2100				
	DAILY min				5				0.1	10	503				
13/1/2006	9:00-12:00	0.35	91	921	25			C**							C**
	12:00-15:00	0.78	148	922	71			A**							A**
	15:00-18:00	1	204	1108	108			B**							B**
	DAILY avg	1	143	957	69	177	337						71	142	
	DAILY max	3	33	204	111										
	DAILY min	0.11	4	454	4										

In the figures presented, typical examples of the daily evolution of the pollutants measured in the living room and the kitchen are given. In figure 1, the distribution of total VOCs in the living is presented for 11/2/06 (Saturday). A double morning peak (2400 μg m^{-3}) appears around 9:00 LST and 12:00 LST which may be attributed to opening of the windows, cleaning and cooking activities in the flat. Concentrations then decrease to 450 μg m^{-3} until 18:30 LST where the inhabitants gather in the living room smoking a number of cigarettes and values reach 4400 μg m^{-3} (22:00 LST). Concentrations then drop gradually to background levels (of the order of 400 μg m^{-3}) after 22:00 LST even though smoking ceased at around 21:00 LST. CO_2 concentrations for the same day follow approximately the same pattern as the total VOCs commencing with 1200 mg m^{-3} in the morning and then dropping to 800 mg m^{-3} at around 12:00 LST. The concentrations then reach a maximum value of 2600 mg m^{-3} at 20:00 LST, sooner than the total VOCs do, while the inhabitants are smoking. After 21:00 LST CO_2 concentrations return to their morning background levels (Figure 2).

Table 4. Measured pollutants' levels at the residence

Date		CO (mg/m^3) LIVING ROOM	TVOCs ($\mu g/m^3$) LIVING ROOM	CO_2 (mg/m^3) LIVING ROOM	TVOCs ($\mu g/m^3$) KITCHEN	$PM_{2.5}$ ($\mu g/m^3$) LIVING ROOM	$PM_{2.5}$ ($\mu g/m^3$) KITCHEN	PM_{10} ($\mu g/m^3$) LIVING ROOM	PM_{10}($\mu g/m^3$) KITCHEN	O_3 ($\mu g/m^3$) IN	O_3 ($\mu g/m^3$) OUT	SO_2 ($\mu g/m^3$) IN	SO_2 ($\mu g/m^3$) OUT	NO_2 ($\mu g/m^3$) IN	NO_2 ($\mu g/m^3$) OUT	NO ($\mu g/m^3$) IN	NO ($\mu g/m^3$) OUT
11/2/2006	DAILY avg	0.1	1310	1236		83	62	125	87	7	43	3	14	5	5	28	32
	max	0.3	4020	2507						15	83	8	32	128	30	76	89
	min	0.01	0.01	842						3	2	2	6	2	0.01	10	12
12/2/2006	DAILY avg	0.2	680	1182		36	22	40	43	13	61	3	17	5	5	28	34
	max	0.4	2315	2246						75	105	9	32	6	7	74	86
	min	0.02	0.01	404						7	27	2	8	2	2	11	13
13/2/2006	DAILY avg	0.1	510	1058	173	34	17	48	31	10	73	3	10	6	6	28	36
	max	0.2	1048	2871	770					45	110	8	23	65	68	77	88
	min	0.01	0.01	705	35					5	19	2	10	1	1	10	11
14/2/2006	DAILY avg	0.02	555	1112	1182	36	83	46	87	13	62	3	16	6	6	30	39
	max	0.1	1369	1986	3013					42	99	9	23	16	19	79	93
	min	0.01	0.5	905	154					4	42	1	5	2	2	11	11
15/2/2006	DAILY avg	0.3	160	1088	641	43	47	51	58	50	80	15	12	46	45	28	35
	max	0.4	989	2411	745					73	117	86	129	177	185	80	96
	min	0.01	0.3	771	51					3	3	1	27	1	2	12	13
16/2/2006	DAILY avg	1	220	1173	510	33	58	58	69	42	55	17	42	81	81	30	40
	max	1.1	1240	2560	1306					62	117	97	138	352	354	84	101
	min	0.1	0.1	706	216					4	3	4	33	1	1	10	9
17/2/2006	DAILY avg	2	580	1269	756	71	25	95	62	31	56	17	44	79	86	30	41
	max	2	1307	2610	1329					156	98	51	137	270	284	99	121
	min	0.04	0.5	905	15					1	1	4	35	1	1	11	8
18/2/2006	DAILY avg	0.4	270	1216	399	33	14	52	47	17	50	17	44	38	42	30	41
	max	1	986	2351	2369					85	124	26	64	95	95	98	132
	min	0.01	0.04	888	37					6	1	5	21	1	1	15	8
19/2/2006	DAILY avg	0.4	320	1135	1098	51	35	83	46	17	36	14	42	34	34	30	39
	max	1	890	2541	4310					26	81	16	48	61	115	95	127
	min	0.01	0.01	806						4	2	4	10	3	2	13	9

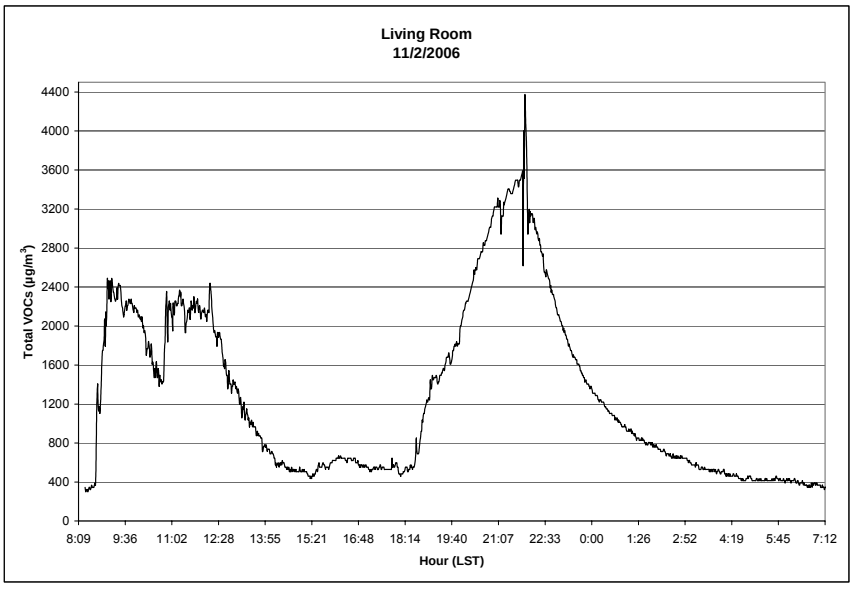

Figure 1. Total VOCs concentrations in the living room for 11/2/06

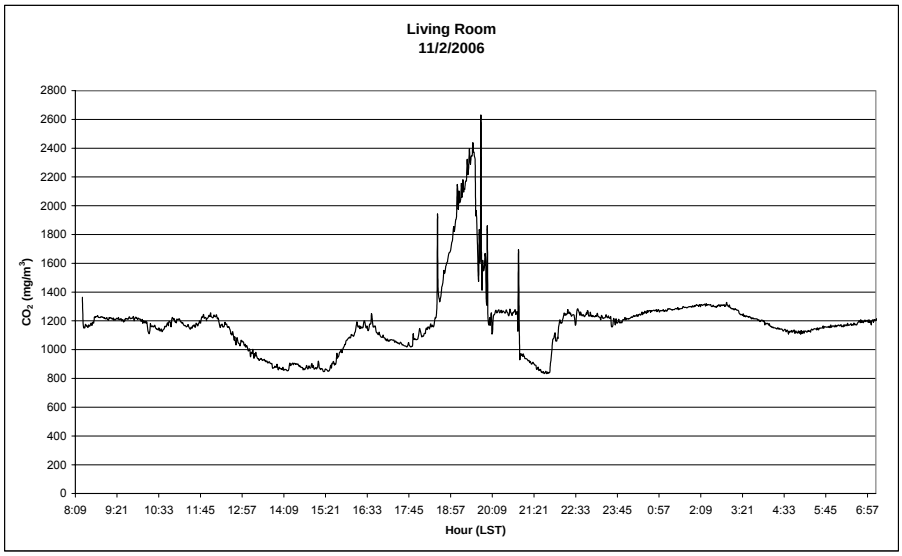

Figure 2. CO_2 concentrations in the living room for 11/2/06

In Figure 3, the total VOCs daily distribution for a typical working day is presented. As can be seen, an early morning peak of the order of 1800 μg m^{-3} appears which is associated with opening of the living room window. Concentrations gradually decrease two hours later to approximately 200 μg m^{-3} and increase slightly when the inhabitants return home from work. At 19:40 LST frying is taking place in the kitchen while all windows are kept closed and concentrations rise instantly to 5500 μg m^{-3}. It is interesting to note that within one hour the total VOCs levels have returned to lower values and remained constant during the night. On the other hand, total VOCs in the kitchen are higher than in the living room during the whole day, figure 4. In the morning when windows are open the concentrations rise to 2200 μg m^{-3} and fall to approximately 500 μg m^{-3} while the house is empty. In the afternoon when there is activity in the kitchen the levels increase with a pronounced peak appearing while cooking. It is noticeable that this peak of the order of 3000 μg m^{-3} is smaller than the respective one in the living room which may be attributed to movement of the polluted air mass out of the kitchen and in to the living room. Finally, at night when no activity is taking place total VOCs levels do not drop below 1500 μg m^{-3}, which may be caused by deposition and re-emission of pollutants from the kitchen walls. In figure 5, the daily evolution of the CO_2 concentrations is presented for the same day as above. It is interesting to see that CO_2 levels drop to 800 mg m^{-3} when the inhabitants are out of the flat and climb up to 1200 – 1400 mg m^{-3} when they are home. The values indicate that CO_2 levels are high but not unacceptable and that they are mostly affected by human presence and not the type of activity except for smoking.

Regarding the 24 hour averaged particulates concentrations measured; it was found that their values varied greatly ranging from 40 to 125 μg m^{-3} (PM_{10}) and 15 to 90 μg m^{-3} ($PM_{2.5}$). In general higher values were observed in the living room, which is associated with smoking events and resuspension because of cleaning and intense activity. Maximum PM_{10} and $PM_{2.5}$ concentrations in the living room were found at Saturday 11/2/06, the day the inhabitants stayed mostly at home and smoking took place, 125 and 85 μg m^{-3} respectively. Maximum PM_{10} and $PM_{2.5}$ concentrations appeared in the kitchen at 14/2/06 a day that frying took place with all openings closed, 85 μg m^{-3} and 80 μg m^{-3} respectively. Minimum PM_{10} and $PM_{2.5}$ concentrations appeared at 12/2/06 because the inhabitants kept the windows open for a longer period and smoking did not occur, while all other daily activities continued as normal, 40 and 35 μg m^{-3} in the living room and 40 and 20 μg m^{-3} in the kitchen respectively.

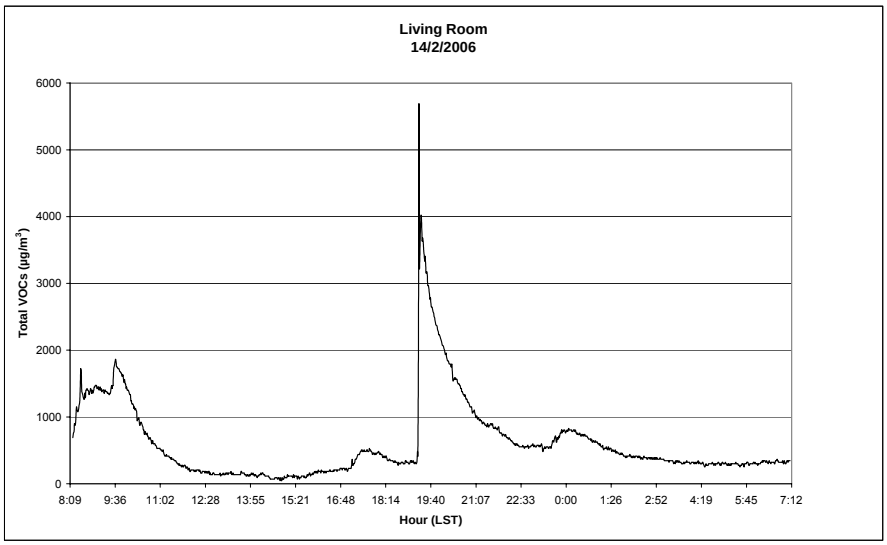

Figure 3. Total VOCs concentrations in the living room for 14/2/06

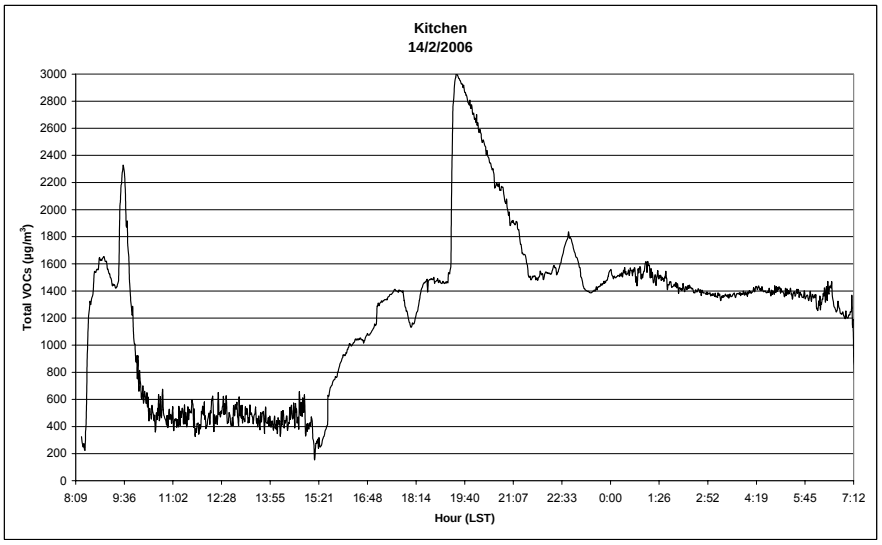

Figure 4. Total VOCs concentrations in the kitchen for 14/2/06

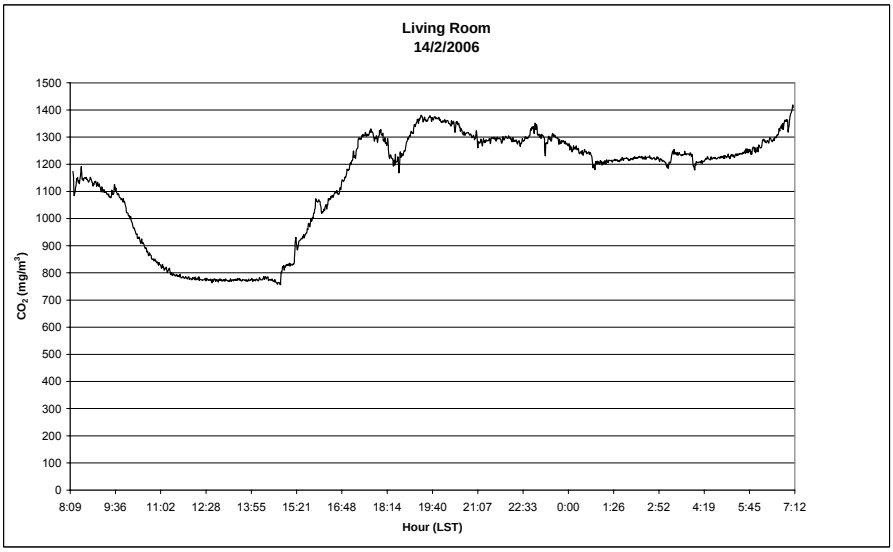

Figure 5. CO_2 concentrations in the living room for 14/2/06

4. CONCLUDING REMARKS

The indoor air quality of two differently used areas, a residence and two offices was assessed during two experimental campaigns performed and the data obtained were very interesting. It seems that the indoor and outdoor air quality of the residence is poor and that the location plays the primary role, i.e., it is a residential area where all buildings use petrol central heating, close to a heavy trafficked road and surrounded by pine trees. Furthermore, total VOCs and CO_2 concentrations in the residence were significantly higher than in the office which may be attributed to the type of activities that took place by the inhabitants, especially cooking and cleaning and the longer time they occupy their home. It seems that deposition of VOCs on the walls is another important process since at night time in the kitchen they maintained their high levels indicating re-emission after the end of cooking. On the other hand the offices had better indoor and outdoor air quality regarding the classical pollutants and TVOCs and CO, CO_2 since the university campus is located at a distance from inhabited areas on the foot of mount Hymettus. However, higher particulate matter values were observed in the two offices which may be associated not only to smoking events but also to poor cleaning of the areas and resuspension because of human activity.

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