Indoor air quality in two different commercial buildings: Part 1: ventilation, temperature, humidity of air and gas concentrations

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ABSTRACT
The main objective of this study was to investigate the Indoor Air Quality (IAQ) in office buildings and to understand better how HVAC (Heating, Ventilation and Air-conditioning) systems work and what their effects are on IAQ over a sustained period. Two French commercial buildings were chosen, located in urban areas of Lyon and Paris, and for one day a month, over the course of 1 year, a number of IAQ related variables were recorded both inside, including the HVAC system, and outside the buildings. Physical parameters of temperature, relative humidity, air flow rate, gas concentration (CO, CO_2, NO_x, HCHO), air bio-contaminants (fungi, bacteria), dust concentrations and air filter efficiencies were evaluated. The results presented in this article show the relationships between HVAC air flow rates and occupant comfort, and illustrate the variation in IAQ for two French commercial buildings. Other data are presented and discussed in Part 2 of the article.

INDEX TERMS
Indoor air quality (IAQ); Air-conditioning systems (HVAC); Commercial buildings; Experimental survey; Gas contaminants

INTRODUCTION
We know that an average citizen spends more than 80% of their time in indoor spaces. In France, a number of studies have been carried out earlier to better understand IAQ in commercial buildings, presenting either results of surveys in air-conditioned buildings or results of comparisons between buildings with or without an HVAC system fitted. Mouilleseaux *et al*. (1993) carried out one of the first and biggest on-site IAQ investigations in 110 air-conditioned buildings located in the Paris area between 1986 and 1991. The results provided a comprehensive IAQ reference for office buildings. It was found that the average temperature and relative humidity were, respectively, 23°C and 40%. Average fungi and bacteria concentrations were respectively 15 and 401 UFC/m^3. Gas concentrations were low: 2 ppm for CO and 767 ppm for CO_2. Due to the large number of buildings selected, this study offers a good overview of general IAQ in office buildings in Paris. However, further measurements and detailed information on the HVAC systems used such as the volume flow rate, the VOCs and the filter efficiency over a long period are required to fully appreciate their influence on the environment and specifically on IAQ. Mouilleseaux *et al*. (1989) and Saude *et al*. (1993) also carried out two interesting studies. Both are based on a comparison of IAQ in air-conditioned and naturally ventilated buildings. The data analysed, especially those cases measured in the air-conditioned building are particularly relevant to the study presented in this paper. The results of the first study carried out over the course of a single month (April) in two office buildings located in Paris, one with an air-conditioning system without recycling and the other naturally ventilated showed mainly higher concentrations of CO, CO_2, particulates and fungi concentration in the naturally ventilated building. However, longer term

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measurements are necessary to incorporate seasonal variations. The second study carried out by Saude *et al*., (1993) is more relevant since it offers a comparison over a full year of IAQ in air-conditioned and naturally ventilated buildings. Parameters recorded in offices in each building including comfort parameters (temperature, relative humidity), gas concentrations (CO, CO_2, NO_x, VOC) and air bio-contaminants (fungi, bacteria) allowed a clear and detailed IAQ analysis. What is important though is that air renewable rates in the offices, air flow rates in the HVAC systems, particulate concentrations in the offices and HVAC systems, and filter efficiencies were not monitored in this study. The measurement and recording of these parameters are extremely important when trying to clearly understand the effect of HVAC on the environment and IAQ. The study carried out by EDF and CETIAT is a wide ranging one, continuously monitoring IAQ in two French commercial offices over an extended period of 1 year and its variation with the seasons, comfort parameters, air filter efficiencies and air flow rates. Results presented in this article show the relationships between HVAC air flow rates and occupant comfort, and illustrate the IAQ variations in two French commercial buildings, based upon contaminant concentrations of CO_2, CO, HCHO and NO_x. Other data are presented and discussed in Ginestet *et al.* (2003).

METHODS

This study has been carried out in two French office buildings, one located in downtown Lyon (13 floors) referred to as Building 1 and the other located in a suburb of Paris (five floors) and referred to as Building 2.

Site Descriptions

Both buildings are located in an urban environment, fitted with an HVAC system and composed of offices with typical desk based activities. Building 1 was built in 1974 and Building 2 in 1997. Offices in the buildings are ventilated with a mixture of fresh outdoor air and recycled air. This air mix comes from an air handling system located on the roof, and is distributed through the offices via fan coil units (Building 1) or through plenums and diffusion units (Building 2). For Building 1, air cooling and heating is achieved with coils fed with cold and hot water, respectively. In Building 2 a reversible air/water heat pump feeds coils of the air handling system to cool or heat the air. With respect to air filtration, in Building 1 the air handling unit includes F6 class bag filters and F7 compact filters mounted in series while in Building 2 G3 panel filters are used in series with F7 bag filters for the recycled air and G4 panel filters with F7 bag filters for the outside air. Filters were changed just prior to commencement of the measurements. Windows of Building 1 are non-opening while those of Building 2 are arbitrarily opened and closed by the occupants. Air is sucked out of the buildings through devices located in the corridors. In Building 1, the air flow rate of the HVAC system is constant while the ratio of recycled air to outdoor air may change depending on outdoor air temperature. In Building 2, the air flow rate of the HVAC system is variable and the ratio of recycled air to outdoor air may change depending on the CO_2 concentration (more or less than 600 ppm) of returned air.

Air Monitoring Protocols

IAQ monitoring along with other measurements have been analysed for one day each month over the course of a year, specifically July 2001–June 2002 for Building 1 and September 2001-August 2002 for Building 2. To ensure consistent results, particularly with respect to the operation of the HVAC system, the same mid-week day was always analysed.

The outdoor environments of both buildings, the HVAC systems and the indoor environments have been investigated. For Building 1 four offices located on the 13th floor were used, and in Building 2 three offices, two located on the top floors and one on the 3rd

floor were used. IAQ in the offices was characterized by temperature and relative humidity of the air, total dust concentrations, air bio-contaminants (bacteria and fungi) and gas contaminants (CO_2, CO, NO_x, HCHO) (AFNOR, 1998). Air flow rates distributed within the offices have also been measured. Similar measurements were made for the HVAC installations, additionally recording air flow rates for outdoor air, supplied air and extracted air. Only CO_2 was measured within the HVAC systems. For each of the monthly 24 h analysis periods, comfort parameters and air flow rates were recorded continuously for the 7 days encompassing this period, and likewise gas contaminants were recorded for 3 days. Air filters have been characterized through on-site and laboratory measurements of fractional efficiency, pressure drop and mass of dust obtained.

RESULTS AND DISCUSSION

Because experimental results in this study are numerous, this paper focuses on the presentation of particular parameters relating to occupant comfort. Those chosen relate to temperature, relative humidity, air flow rates in the HVAC systems and offices and the measurement of gas contaminants (CO, CO_2, NO_x, HCHO) in offices. For the monthly variations, average values were calculated from each analysis period using only the data recorded during office hours (9–5p.m.).

Temperature, Relative Humidity and Air Flow Rates in HVAC Systems and Offices

For Building 1 and 2, no significant changes were seen in the air flow rates of the air handling systems over the course of the year, any fluctuations being due to normal experimental uncertainties. Figures are available in Ginestet *et al.* (2003).

Handling systems for both buildings are designed to work with a recycling mode. For Building 1, the recycling mode is used to cool down the building. When the extracted air temperature is below the outdoor air temperature and greater than 23°C, the recycling mode of the handling system operates, resulting in supplied air composed of 30% extracted air and 70% outdoor air. In normal operation, there is no recycling and the supplied air is composed of 100% outdoor air. For Building 2, the recycling mode is based upon the CO_2 concentration of the extracted air. When the CO_2 concentration is below 600 ppm, a fraction of the extracted air is recycled. The handling system of Building 2 also has a free-cooling system, best suited to Spring or Autumn seasons, to supply outdoor air into the building without any pre-heating or pre-cooling. Generally speaking, for both buildings, the temperature and the relative humidity of the supplied air stay constant within office hours, resulting in satisfactory comfort levels for the occupants. This was always observed, independent of the seasons.

As an example of the results recorded for a summer's day (July 2001) with recycling mode activated, Figures 1 and 2 show the temperature and relative humidity variations of supplied, extracted and outdoor air for Building 1. On this day, the outdoor temperature continuously increased over the day (Figure 1) while the relative humidity of the air decreased (Figure 2) as expected for a sunny day. When the outdoor air temperature almost reached the extracted air temperature at about 13h30 (Figures 1 and 2), the recycling mode and cooling battery are operated, resulting in a temperature decrease and relative humidity increase of the supplied air. In Figures 3 and 4 showing temperature and relative humidity variations in the course of a typical winter's day (January 2002) of supplied, extracted and outdoor air for Building 2, it can be seen that the HVAC system started to operate at 03h30 in the morning, supplying air at a high temperature 4 h before the arrival of occupants.

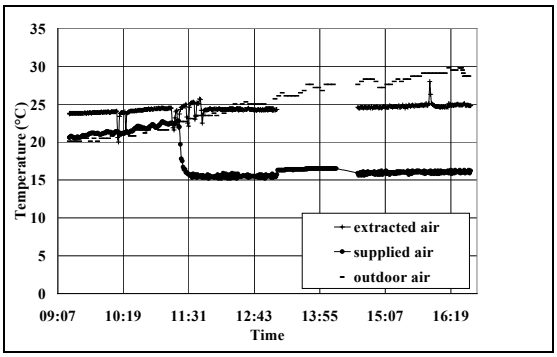

Figure 1 HVAC temperature Building 1—12 July 2001.

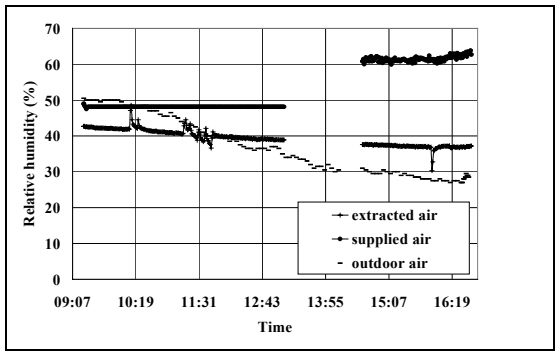

Figure 2 HVAC relative humidity Building 1—12 July 2001.

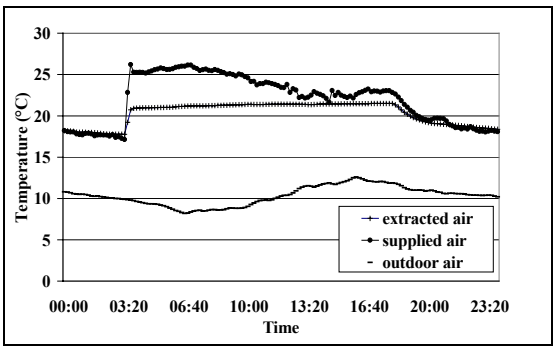

Figure 3 HVAC temperature Building 2—29 January 2002.

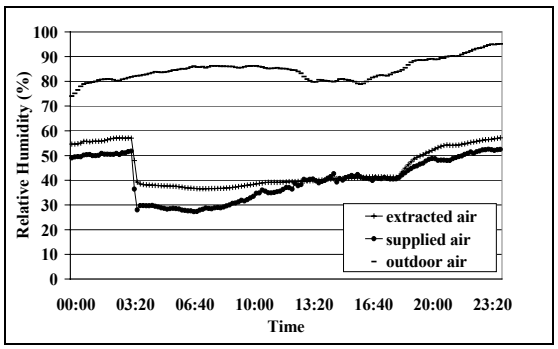

Figure 4 HVAC relative humidity Building 2—29 January 2002.

Table 1 summarizes air volume flow rates supplied to the offices expressed according to the number of office occupants (m^3/h/person) for both buildings. For Building 1, the air volume flow rates for each office remain constant over the course of the year but they vary between 130 and 160 m^3/h/person depending upon the office. For Building 2, the air volume flow rates in each office vary more widely over the year: 26 to 200 m^3/h/person. For both buildings, the air volume flow rates in the offices meet or exceed the French regulation of 25 m^3/h/person.

Table 1 Air flow rate supplied to offices for Building 1 and Building 2

Building 1 (m^3/h/person)				Building 2 (m^3/h/person)			
Date	Office 1	Office 2	Office 3	Date	Office 1	Office 2	Office 3
12/07/01	135	140	160	25/09/01	55	100	58
17/10/01	130	137	158	29/01/02	54	100	55
23/01/02	130	136	156	23/04/02	51	50	26
17/04/02	132	140	158	30/07/02	96	65	71

The daily variations of temperature and relative humidity of air recorded in the three offices of both buildings over the year were small: 1–5°C for the temperature and a few percentage points for the relative humidity, as illustrated in Table 2. The smallest values were observed in winter. Air temperature and relative humidity of air were well controlled in both buildings, resulting in satisfactory comfort levels for occupants. According to (ASHRAE, 1992), satisfactory comfort is achieved if the air operative temperature values are between 20°C and 24°C and those for relative humidity of air are in the range 30–70%. For both buildings, it can then be concluded that temperature is adjusted but the relative humidity is low, especially in winter. This can be attributed to the fact that there was no humidification system in

Building 1, and that the system in Building 2 did not operate.

Table 2 Average temperature (°C) and relative humidity (%) in offices in Buildings 1 and 2

Building 1							Building 2						
	Office1		Office 2		Office 3			Office1		Office 2		Office 3	
Date	Temp	RH	Temp	RH	Temp	RH	Date	Temp	RH	Temp	RH	Temp	RH
12/07/01	26.0	36.0	24.0	36.0	22.5	42.0	25/09/01	25.1	39.5	23.7	41.5	23.7	46.2
20/09/01	21.5	47.0	21.0	48.0	21.0	46.0	27/11/01	23.2	33.3	23.3	31.7	*n/a*	38.1
20/11/01	21.0	19.0	21.0	21.0	20.5	20.0	29/01/02	23.1	37.0	23.3	35.1	21	42.2
23/01/02	22.0	27.0	21.0	28.0	20.5	27.0	19/03/02	23.6	43.4	24.0	40.5	22.7	48.2
20/03/02	24.0	44.0	22.0	43.0	23.0	41.0	28/05/02	23.2	38.1	22.0	38.9	22.8	42.5
15/05/02	25.0	28.0	23.5	37.0	22.5	34.0	30/07/02	25.2	46.8	25.0	43.8	24.8	51.4

IAQ Monitoring Based on Gas Contaminants in French Offices

The experimental standard (AFNOR, 1998) for IAQ diagnostics in commercial buildings indicates the global parameters that are to be measured in assessing thermal comfort and IAQ. CO, CO_2, NO_2 and HCHO are the main gas contaminants to measure in such a building to evaluate its IAQ. In this study, these parameters were assessed continuously for 24 h once a month for 1 year. Table 3 gives average daily concentrations of CO_2, NO_2 and HCHO for each month, the averages being calculated from data variations recorded during office hours (9–5pm). No CO data are included because of the insignificant and unchanging values recorded.

Table 3 Eight hour average gas concentrations (CO_2, NO_2, HCHO) for offices in Building 2

Dates	CO_2 Concentrations [ppm]			NO_2 Concentrations [ppb]			HCHO Concentrations [mg/m^3]		
	Office 1	Office 2	Office 3	Office 1	Office 2	Office 3	Office 1	Office 2	Office 3
25/09/01	628	577	678	6.12	4.00	9.19	0.379	0.418	0.503
23/10/01	731	590	586	3.62	7.90	9.67	0.163	0.170	0.182
27/11/01	988	813	855	8.45	7.30	9.89	0.276	0.249	0.059
18/12/01	866	893	1016	11.36	10.17	11.98	0.133	0.222	0.071
29/01/02	*n/a*	696	807	*n/a*	5.47	9.60	*n/a*	0.169	0.290
26/02/02	673	754	643	10.80	5.55	7.60	0.191	0.349	0.186
26/03/02	798	433	*n/a*	6.16	11.25	*n/a*	0.447	0.212	*n/a*
28/05/02	581	573	*n/a*	10.34	28.22	*n/a*	0.033	0.068	*n/a*
25/06/02	458	575	716	7.95	22.97	*n/a*	0.100	0.070	0.133
16/07/02	472	448	418	5.71	11.48	12.99	0.200	0.188	0.020
27/08/02	422	424	420	4.80	7.05	7.90	0.354	0.138	0.050

Due to the very high air volume flow rates supplied to Building 1, gas contaminant concentrations were very close to those of the outside air and are not presented in this paper. In the three offices of Building 2, for the complete year, average CO_2 concentrations stayed below 1000 ppm, a guideline given by the World Health Organisation (WHO) and by the French circular dated 9 May 1985, except in December where higher concentrations are reached due to low air flow rates. Indoor CO_2 concentrations are always above or close to those of outside air and constant at approximately 400 ppm. As shown in Table 3, higher average CO_2 concentrations (1.5 to 2 times those of outside) are recorded in winter. This can be explained by the HVAC system using its recycling mode. The summer holidays result in normal occupants being away from the office, and average CO_2 concentrations are close to those of the outside. These data confirm previous results indicating CO_2 as a good tracer of human occupancy in offices. The NO_2 values recorded during the four seasons within the three offices were always under 80 ppb, a guideline given by the 'Conseil Superieur d'Hygiène Publique de France' CSHPF. NO_2 sources coming mainly from industrial and car

emissions, peak at 25–30 ppb in summer when high values were recorded outside. Contrary to CO_2 and NO_2 concentrations observed, HCHO concentrations recorded during the experimental study within the three offices were often greater than the WHO IAQ guideline of 0.100 mg/m^3 (8 h), the highest values being recorded in September. For this day, air flow rates supplied into offices 1, 2 and 3 are respectively 55, 100 and 58 m^3/h/person, which is at least twice the French standard value. Despite these air flow rates, high HCHO concentrations are observed. Generally speaking, average HCHO concentrations are not correlated with air flow rate. As a result, even higher than recommended ventilation rates can appear insufficient to maintain HCHO concentrations within specified guidelines for new buildings.

CONCLUSION

The study provided an insight into how IAQ varies over a year for two specific French commercial buildings and how their HVAC usage patterns affect this variation. Results presented in this paper (comfort parameters, gas concentrations and air flow rates) show that both HVAC systems considered have satisfactory usage patterns with respect to IAQ. During all recording periods they maintained the temperature and relative humidity within the range of comfort values regarded as satisfactory by (ASHRAE, 1992). Gas concentrations in the offices were globally acceptable with the exception of HCHO concentrations in Building 2 that were above WHO guidelines despite higher than normal air flow rates. Further investigation is necessary, but this work already allows one to point out that high air volume flow rates in new buildings might be insufficient or not well adapted to control and maintain HCHO concentrations below stated guidelines. Additional results presented in Ginestet *et al.* (2003) show the positive effect of air filtration on IAQ (air bio-contaminants and dust concentrations). The IAQ of a third commercial building should be carried out soon and will be used as a means to confirm the content of this paper.

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