Indoor air quality in residential buildings: costs, effects and benefits of mechanical ventilation systems

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ABSTRACT

The presence of high levels of urban pollution imposes at the international level the need to think again about the type of ventilation systems in residential buildings. This has to be done in order to provide a better IAQ level. Natural ventilation cannot guarantee either the correct change of air inside the buildings or a good IAQ level, as there is no possibility of checking the supply and extraction airflow rates in any thermo-hygrometric condition. The high level of pollution in urban air, due to the traffic, civil and industrial processes of combustion in big metropolis, causes a second problem, stronger than the first one: natural ventilation in these kinds of conditions implies a dangerous and uncontrollable exposure of people to substances of human origins that are injurious to health. For these reasons the use of mechanical ventilation as a part of the technical equipment of buildings seems to be necessary for the future. In this way two effects would be produced at the same moment: the continuous extraction of smells and steam caused by human activities and the supply of treated outdoor air into the civil rooms, to achieve the best control of the quality of the internal air. In this direction the revision of international technical laws concerning the ventilation parameters must be seen and a further acceleration of this process should be provided. In this paper some analysis about the levels of pollutions in external air of European cities are carried out and considerations about costs, effects, benefits, complexity of installation and performances of mechanical ventilation systems, in terms of IAQ, for residential buildings are developed as well.

INDEX TERMS

Air pollution; PM_{10}; Natural and mechanical ventilation; Filtration; Residential building; IAQ

INTRODUCTION

The effects of air pollution on human health depend on the chemical and physical substances, on the levels and time of exposure, on the susceptibility of the exposed population, on the predisposition to certain diseases (head ache, etc.), and on the age, sex and social conditions. People suffering from respiratory conditions such as asthma, both the very young and old, are particularly at risk. Environmental Protection Agency studies of human exposure to air pollutants indicate that indoor levels of pollutants may be two to five times and occasionally more than 100 times, higher than outdoor levels. Limiting this study to residential buildings, carbon dioxide and carbon monoxide are the main indoor pollutants. The first is produced by human activities and by the heating and cooking ones; the second is linked with combustion processes. Apart from other gases, whose presence is limited at particular geographical areas (radon) or at the employment of particular furnishing (formaldehyde), the main result of a polluted ambient is the general dissatisfaction of occupants caused by smells and poor oxygen concentration. In Table 1 a list of emissions due to human metabolic activities is reported.

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In Table 2 threshold values according to different international standards are listed. In almost every country people do not take care of this kind of problem, so in residential buildings, usually thought as ‘poor buildings’, ambient ventilation is carried out by opening doors and windows and seldom by more efficient systems. French regulations make exception: in this case designers must estimate the best exchanged rates to assure comfort inside the building; therefore, they must plan the installation of ventilation systems, natural or mechanical. With the first solution, the rooms would have openings in the facade of the buildings (i.e. connected with the blind boxes) would extract air naturally by ducts and collected to the roof. With the second solution, the most used in France due to economic and energetic advantages, mechanical systems extract air continuously from inside and eject it by a special fan to the external environment. The most developed systems use a second fan to collect into the flats external air, filtered and pre-heated by a static heat recovery; we will refer our following analysis to this type of systems. In this way about 50% of energy saving is obtained. Italian law imposes for residential buildings a change rate of 0.5 volume per hour. If openings’ permeability does not guarantee this rate, the Italian regulation states clearly the need to install continuous mechanical ventilation system. Other specific European regulations are not known to us. When usual air pollution levels of the big world metropolis are examined, the problem becomes harder. In this case the air exchange, obtained both by natural methods (just by the openings of doors and windows) and by technical plants, causes the worsening of IAQ. This is attested by a Japanese research that underlines the direct relation between outdoor and indoor pollution (Lee *et al.*, 1997, 1999) in unfavourable conditions. In this paper, economic and technical considerations regarding these problems and its solutions are discussed.

Table 1 List of common pollutants in residential buildings [emission (μg/h)]

Pollutant	Emission	Pollutant	Emission	Pollutant	Emission
Acetaldehyde	35	Chloroform	3	Tetracloretano	1.4
Acetone	475	Dioxane	0.4	Tetracloretilene	1
HN_3	15 600	Hydrogen sulphide	15	Toluene	23
Benzene	16	Methane	1710	Tricloretano	42
2-Butanone	9700	Methanol	6	Vinyl chloride	0.4
CO_2	32 000 000	Methylene chloride	88	Xylene	0.003
CO	10 000	Propane	1.3		

METHODS

Our work is part of an Italian project whose aim is collecting data that should be submitted to the authority in order to formulate an extensive law about IAQ for residential buildings. It has been developed through the analysis of outdoor pollution concentrations in the biggest cities of the world and of the limits imposed by WHO and European Directives.

RESULTS

Some studies (APHEIS, 2001) show that in 26 European towns pollution causes more deaths than car accidents, leukaemia and AIDS. All around the world many cities (Bangkok, Bombay, Budapest, New Delhi, Jakarta, Karachi) are polluted by lead emissions 30 times higher than limits imposed by WHO. Moreover, emissions of SO_2, CO, O_3 in Mexico City are two times higher than the limits accepted; the situation is similar for Seoul, Peking, Shanghai, Cairo, Manila and Los Angeles. Every year millions of people die or suffer serious health effects for indoor and outdoor air pollution: mainly respiratory diseases, asthma, chronic obstructive pulmonary disease, cardiovascular disease, acute respiratory infections and lung cancer. Other studies (APHEA, 2001; SIDRIA, MACBETH, MISA) confirm the relation between air pollution episodes and increased prevalence of topic sensitisations, allergic symptoms, diseases, reduced lung function, increased cardiovascular hospital admissions and mortality, even caused by leukaemia for those children who live near main motorways. Moreover, heart failure deaths were found to be responsible for about 30% of the cardiovascular deaths related to particulate matter, SO_2, CO and NO_2 (Hoek *et al.*, 2001).

Table 2 List of common pollutants in residential buildings

	Canadian	WHO/Europe	NAAQS/EPA	NIOSH	OSHA	ACGIH	MAK
Formaldehyde	0.1 ppm [L]	0.081 ppm [30 min]		0.016 ppm 0.1 ppm [15 min]	0.75 ppm 2 ppm [15 min]	0.3 ppm [C]	0.5 ppm 1 ppm [5 min]
Carbon dioxide	0.05 ppm [L][b]			5000 ppm 30000.ppm [15.min]	10000.ppm 30000 ppm [15 min]	5000 ppm 30000 ppm [15 min]	5000 ppm 10000 ppm [1 h]
Carbon monoxide	11 ppm [8.h] 25 ppm [1.h]	87 ppm [15 min] 52 ppm [30 min] 26 ppm [1.h] 8.7 ppm [8 min]	9 ppm[g] 9.ppm [1 h][g]	35 ppm 299.ppm [C]	35 ppm 200 ppm [15 min] 1500 [C]	25 ppm	30 ppm 60 ppm [30 min]
Nitrogen dioxide	0.05 ppm 0.25 ppm [1 h]	0.2 ppm [1 h] 0.08 ppm [24 h]	0.08 ppm [1.y]	1 ppm [15 min]	1 ppm [15 min]	3 ppm 5 ppm [15 min]	5 ppm 10 ppm [5 min]
Ozone	0.12 ppm [1 h]	0.08–0.1 ppm[1 h] 0.05–0.061 ppm [8 h]	0.12 ppm [1.h]	0.1 ppm [C]	0.1 ppm 0.3 ppm [15 min]	0.05 ppm 0.2 ppm [15 min]	0.1 ppm 0.2 ppm
Particulate <10 MMAD[d]	0.1 mg/m^3 [1 h] 0.040 mg/m^3 [L]				5 mg/m^3	3 mg/m^3	
Particulate[e] <10 MMAD[d]			0.05 mg/m^3 [1.y] 0.15 mg/m^3 [24 h][g]			10 mg/m^3	
Total particulate					15 mg/m^3		
Sulphur dioxide	38 ppm [5 min] 0.019 ppm	0.19 ppm [10 min] 0.13 ppm [1.h]	0.03 ppm [1 y] 0.14 ppm [24 h][g]	2 ppm 5 ppm [15.min]	2 ppm 5 ppm [15 min]	2 ppm 5 ppm [15 min]	2 ppm 4 ppm [5 min]
Lead		0.5–1.0 mg/m^3 [1 y]	1.5 mg/m^3 [3 m]	<0.1 mg/m^3 [24 h]	0.05 mg/m^3	0.05 mg/m^3	0.1 mg/m^3 1 mg/m^3 [30 min]
Radon		2.7 pCi/l [1 y]	4 pCi/l [L][f]				2 ppm

Values refer to: Canadian: Recommended maximum exposures for residences, WHO/Europe: Environmental (non industrial) guidelines 1987 (Denmark), NAAQS: Criteria for outdoor air developed under the Clean Air Act by the US EPA, NIOSH: Recommended maximum exposures for industrial environments, OSHA: Enforceable maximum exposures for industrial environments, ACGIH: Recommended maximum exposures for industrial environments (at normal work conditions, 40 h a week), MAK: Recommended maximum exposures for industrial environments (Deutsche Forschung Gemeinschaft), [b]: limit of 0.05 ppm because of carcinogenic effects. Total aldehyde limited at 1 ppm, [c]: Carbon monoxide concentration in non-industrial environments is lower, [d]MMAD=mass median aerodynamic diameter in micron, [e]: unhealthy particles not otherwise classified, [f]USEPA enacted a value like 4 pCi/l for concentration indoor, [g]: cannot be exceeded more than once a year, [C]: peak rate, [L]: long term

Furthermore, indoor air pollution is the primary cause of occupational chronic respiratory disease each year, estimated in 50 million cases. These are widespread, debilitating and affect people in their social and economic prime of life. All pollution products have negative effects on health, but recently attention has been focussed particularly on damages caused by PM10, ozone and nitrogen dioxide. Some data (see Table 3) can better clarify the situation. Besides, Table 4 shows the average of outdoor pollution checked in some big cities, while Table 5 describes parameters recommended by national and international regulations. It is important to underline that a homogeneous procedure to monitor air quality in the world does not exist. Independently of this consideration, the reported data are very significant, because they summarize the most dangerous pollutants and the reference law levels. Something must be stated about TSP and PM10 survey: we have not found data about PM10 concentration in the world cities; in Italy and in Europe PM10 data have replaced TSP ones because EU Directives consider the TSP survey insignificant, as already done by Italian law in 1994. PM10 are the most dangerous in total suspended particulates due to the high easiness and therefore the possibility to be inhaled into the lungs.

Table 3 Effects of pollutants on human health

Research	Places ref.	Pollution rate	Type of pollution	Effects:
APHEA		+100 µg /mc/day	TSP	6% excess of deaths
		+50 µg/mc/day	PM10	2% excess of deaths
		+50 µg/mc 7 hour max	O_3	3% excess of deaths
CNR	Rome	Simple exposure	PM10	5.1% of total death for respiratory diseases
	Turin	Simple exposure	PM10	5.3% of total death for respiratory diseases
	Naples	Simple exposure	PM10	5.3% of total % of death for respiratory diseases
	Boulogne	Simple exposure	PM10	5.1% of total death for respiratory diseases
	Florence	Simple exposure	PM10	4.0% of total death for respiratory diseases
	Genoa	Simple exposure	PM10	3.9% of total death for respiratory diseases
	Palermo	Simple exposure	PM10	3.5% of total death for respiratory diseases
	Milan	Simple exposure	PM10	4.1% of total death for respiratory diseases
WHO	France, Switzerland and Austria		External pollution	40 000 death/year
	France, Switzerland and Austria	Simple exposure	PM10	21 000 death/year
	Asia		External pollution	500 000–1 000 000 excess deaths/year
	Sub-Saharan (Africa)		External pollution	300 000–500 000 excess deaths/year
	San Paulo (Brasil)	+75 µg/mc	NO_2	+30% deaths from respiratory illness in children under five years of age

APHEA, Alaska Private and Home Educators Association; CNR, Nat. Research Centre—Italy; WHO, World Health Organization.

Besides they have a very small diameter and they can remain for a long time on air due to their weight. Other studies on air pollution survey point out that PM10 rates are about 60–70% of TSP rates. Tables 4 and 5 show the need to think again about ventilation processes for civil buildings due to the real risk for human health. Besides some studies from Korea and Hong Kong tried to determine the relationship between indoor and outdoor air quality (Lee *et al.*, 1997, 1999). The ratio is often quite near 1 and it depends on the rate of exchange between these two environments. Moreover, the results show that in a house with a passive ventilation system, there is much risk of indoor air pollution in spring, autumn and when air is conditioned, and the concentration of PM10 decreases with enhancing vertical height.

DISCUSSION

It is a fact that natural ventilation systems do not guarantee a good level of IAQ, especially if outdoor pollution is considered. In this case it is not possible to control exchanged air rate and extract indoor pollutants; at the same time there is the risk to introduce dangerous substances in high daily occupation environment. Mechanical ventilation systems, in residential buildings, have to be modified with the aim to reduce the concentration of different kinds of outdoor pollution in supply air. In particular, PM10 pollution has to be reduced, because in Italy they are the most important factor of urban air quality. Not considering other gases, whose reduction must be made by chemical processes, mechanical ventilation systems may be easily adapted in order to decrease PM10 concentration in renewal flow rate of residential buildings.

Table 4 Pollutant concentration in urban air for different cities

Unit	mg/mc	µg/mc		µg/mc	µg/mc		µg/mc		µg/mc	
Pollutant	CO	NO_2		TSP	PM10		SO_2		O_3	
Cities	average in 1day*	average in 1H*	average in 1 year**	average in 1 year**	average in 1 year***	average in 1day*	average in 1day*	average in 1 year**	average in 1day*	summer*
Turin	4	74,9	np	151	63	63,8	17,8		66	111,7
max. measured values	19,8	193,9				180	81,4		217,4	217,4
Florence	2,7	70,1		np	26-51(*)	40,3	7,7		79,5	114,3
max. measured values	8,7	141,4				182,4	40,1		210,7	210,7
Genoa	np	np		np	32-72(*)	np	np		np	np
Rome	5,4	85,8	np	73	27-55(*)	50,6	8,9		np	np
max. measured values	18,5	150,6				124,4	18,5			
Milan	4	86,5	248	77	48	45,2	18,4	31	np	np
max. measured values	12,3	214				126,4	90			
Naples	np	np		np	41-75(*)	np	np		np	np
Bologna	2,4	60,1		np	56	41,2	8,5		75,9	111,2
max. measured values	11,1	120,4				122,9	50		215,7	215,6
Palermo	2,1	61,3		np	25-47(*)	42,9	12,5		np	np
max. measured values	8	137,8				203,3	63,8			
Verona	2,5	57,8		np	np	36,5	6,6		73,8	117,6
max. measured values	10,2	161,3				122,4	33,8		226	225,6
Ravenna	1,8	60,5		np	np	59,1	19,6		np	np
max. measured values	7	175				216	83			
Rio de Janeiro			np	139				129		
Shanghai			np	249				np		
Athens			64	178				34		
Calcutta			34	375				49		
Mexico City			130	279				74		
Manila			np	200				33		
Singapore			30	np				20		
Barcelona			43	117				11		
Bangkok			23	223				11		
London			77	np				25		
New York			79	np				26		

*1995-1999 years(MISA), ** 1990-1995 years(WHO), ***2000-2001years(Min. Ambiente), (*)ref. several observatories

Table 5 Pollutant concentration limits

Unit		mg/mc	µg/mc	µg/mc	µg/mc	µg/mc	µg/mc
Pollutant		CO	NO_2	TSP	PM10	SO_2	O_3
levels value by 99/30 CE	1 year		40		40	20	
	1 day	10		90-180	50	125-250	200
	1 hour	15-30	200-400			350	180-360
levels value by WHO	1 year	0,5-7	40	90-180		50	10-100
	1 day	10				125	120
	1 hour	30	200			500 (10 min.)	

Towards this aim, the installation of EU6–EU8 classified filters, according to EN 779, is sufficient. In this way, PM10 concentration in renewal flow rate decreases of 60–70% compared to the outdoor one: for the Italian cities this would mean a concentrations level under the limits imposed by the law. For the other towns, there are no data on PM10, but we can consider that they are 60–70% of TSP. In this case, with mechanical ventilation systems equipped with EU6–EU8 filters, the PM10 concentration in supplied renewal air to the buildings can be reduced under the limits shown by WHO and 99/30CE (i.e. for Athens the concentrations in dwellings could be about 50 μg/m^3, for Calcutta about 112 μg/m^3, for Rio de Janeiro about 42 μg/m^3, for Shanghai about 75 μg/m^3, for Mexico City about 84 μg/m^3, etc.). Particular systems for the reduction of other pollutants could be developed. This approach guarantees better living conditions in residential premises. From an economic point of view, the installation of a static heat recovery ventilation system for a medium size flat (100 m^2) involves an initial investment of about 1500 Euros, ducts included. Systems for apartment blocks exist: their cost becoming cheaper. Even if the system seems expensive, the heat recovery permits a 50% saving of ventilation energy need. This means, i.e. for Northern Italy, France and Germany, a savings of 2500 kWh for heating, in a year (for a 100 m^2 flat). By considering a cost of 0.15 Euros/kWh for heat production, a saving of 375 Euros/year is calculated for each flat. From the management point of view, the cost of electric energy is linked with the work of two fans: this causes an estimated expense of 1000 kWh per year with the use of high efficiency filters (EU6–EU8). Thus, the real saving is reduced at 225 Euros. The data exposed should not be analysed only with economical point of view: their importance is strongly connected with the need of good IAQ level, and moreover with the lowering of dusts and the comfort that can be achieved. The data do not consider the aspects regarding the energy saving during summertime, in case of conditioning.

CONCLUSION AND IMPLICATIONS

The study and the use of new mechanical ventilation systems for both heating and cooling in dwellings are needed. This is caused by the pollution of outdoor air whose level, in the biggest towns of the world, is normally higher than the limits suggested by medical specialized literature.

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