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ENERGY SAVING AND DYNAMIC CONTROL OF HVAC SYSTEMS IN OPERATING THEATRE: AN EXPERIMENTAL APPROACH

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ABSTRACT
In this paper the problem of anaesthetic gases dilution in operating theatres has been examined, by experiences carried out in a full scale testing room. The performance of two different HVAC plants have been compared, one of them working in static conditions at 20 external air changes per hour, whereas the other has been dynamically driven by an automatic control system between 10 and 20 external air changes per hour.

In the latter case, the flow control operate as a function of the concentration level of tracer gas, simulating a pollutant, sampled in real time by a suitable monitoring system. The results demonstrate that a dynamic HVAC system can guarantee good environmental conditions and satisfactory comfort, as well as remarkable energy savings.

KEYWORDS
Air quality, Energy, Full-scale experiments, Tracer gas

INTRODUCTION
Goal of a ventilation system, pumping external air in a confined environment, is the smell and pollutants control, devoted to maintain acceptable internal conditions in terms of safety and comfort. Nevertheless, the flow rates are calculated using physical models, which cannot take into account the real characteristics of the pollution phenomena and of the behavior of ventilation systems designed to face them. The simpler analytical models, based on macro-balancing, refers to two basic hypotheses, concerning perfect mixing and perfect removal (slug flow) respectively. Both the models, applicable in non-steady-state conditions too ([1]), provide numerical results that, usually, greatly differs from experimental ones. In the first case, in fact, the concentration levels are uniformly distributed and constant in space; whereas in the second case, if the source is uniformly distributed, the same levels vary linearly from the inlet location to the outlet position. CFD procedures, using finite volume analysis, provide more detailed information ([2],[3] e [4]).

Because of such limits, the considered problems are solved in practice by a prudent plant over dimensioning, in order to be able to set high number of air changes per hour. As a counterpart this solution, applied especially in critic conditions and in rooms dedicated to hazardous production processes or to medical activities, causes high energy costs. A supplemental problem comes from the limited knowledge of diffusion process of airborne biological particles (i.e. number and distribution of cellular colonies produced in an operating theatre as a consequence of surgical activity) or of the real amount of anaesthetic gas dispersion in the same conditions. These aspects make the drawbacks of a theoretical analysis more evident and severe. In previous literature ([5],[6] e [7]) the biological aspect has been investigated, trough analytical modelling, with specia' attention to biocontamination effects in rooms devoted to accommodate patients submitted to marrow transplantation. However, even though the gas or particles dispersion phenomena have been focused in many papers, they have not already quantitatively and analytically described definitively and in a satisfactory way.

To overcome the above mentioned drawbacks experimental activities have been carried out on real models, built in 1:1 scale, representing rooms whose safety conditions can be affected by the presence of pollution of whichever origin. Such models utilize a test room, where indoor climate is guarantee by a controlled parameter HVAC system (air flows, temperature, humidity, etc.), submitted to controlled process of pollutant dispersion as well. The concentration field of such pollutants is determined by a monitoring system as a function of time and space coordinates, together with the other physical, chemical and thermodynamic variables characterizing the environment under test. Analogously, thermal and electrical energy flows are measured continuously.

Since the HVAC system of test room can produce variable air flows, in order to maintain a constant, known and acceptable level of pollution in the test room, the performance of dynamic ventilation systems can be studied and quantified.

In this paper the laboratory activities relative to this subject are described, with special regard to the detection and removal of gases in operating theatre.

DESCRIPTION OF THE TESTING SYSTEM

In order to carry out the laboratory experiences, an experimental system has been set up in the establishment of Busi Impianti spa, in the city of Bologna (Italy). This system is composed of:

-a testing room

-a HVAC system

-a monitoring system

-a control unit

The testing room was conceived to recreate in full scale a large variety of confined environments, having dimensions between 4.80x4.80 *m* (height 3.30 *m*) and 7.20x6.60 *m* (height 3.30 *m*).This room has a modular structure, geometrically and dimensionally variable. It is composed of a number of panels which can be either blind or can be equipped with supply and extraction air devices provided with flexible ducts connected to the ventilation plant. Some panels can also be trasparent in order to allow the observation, from the outside, of both the testing room and the film/fotograph shooting.

Caused the easily removable and substitutionable panels, it is possible to experiment more solutions of air conditiong in the same room by recomposing the positioning of the supply and extraction air grilles or by varing their number. Furthermore, all grilles are equipped with motorized shutters for the remote control of the air flow, supplied or extracted. The same criteria of modularity and flexibility were applied to the construction of both ceiling and entries. In this way, it is possible to simulate bacterial contamination phenomena, dust and gas pollution coming from surroundings.

The all-air conditioning plant is able to control air flow rates, temperature, relative humidity and pressure, independently of the outdoor values. The supplied air can be enriched with either tracer gases or dirt particles at prearrangeble concentration and density, in order to allow the simulation of the environmental pollution processes, using the same air conditiong system. Another system, the second one, independent of the first, allows the emission of other tracer gas in any part of the environment.

In both ways, it is possible to identify and visualize the air ways moving inside the room, and identify the presence of non-moving air zones. Therefore it is possible to study the diffusion of pollutants for different outdoor air flow rates.

In detail, the following thermodynamical, physical-chemical and functional properties are costantly monitorized:

1. test room indoor temperature
2. external air temperature
3. test room indoor pressure
4. external air pressure
5. internal air relative humidity
6. external air relative humidity
7. indoor air velocity field
8. test room pollutant gas concentration field
9. particles concentration field
10. outside air flow rate
11. extraction air flow rate
12. air flow rate for single grille
13. stubbed filter grade
14. thermal and refrigerating energy consumed by the HVAC system

15. electric energy consumed by the HVAC system
16. opening status of the entries

On the other hand, the air flow directions for single grille are manually controlled.

An appropriate system composed of a sensors set and a data acquisition apparatus interfaced to a PC, monitorally represented and memorized. In this way, it is possible to compare the obtained results with other from numerical simulation procedures.

A computer supervisor allows the modification of any single system parameter through a user friendly video interface. As previously mentioned, we have at our disposal a variable air flow plant. All data transferred to the control system can be elaborated to automatically vary the configuration of the environmental ventilation apparatus, functioning according to specific prearranged algorithms.

Therefore, this plant is able to determine, inside the test room, the desired microclimatic conditions, in thermalhygrometrical terms and determine also, the concentration level of dirt particles or toxic substances.

DYNAMIC CONTROL OF HVAC SYSTEM IN AN OPERATING THEATRE

It is well known that during an operating activity, a not negligible quantity of anaesthetic gas is released to the environment. These could cause explosion dangers and health damage to the medical personal, because of their exposure to the outlet gas apparatus.

The experimental system object described above was to test the efficiency of possible ventilation plants of an operating theatre. First, to measure the levels of anaesthetic gas concentration at the places occupied by the medical staff. In the second place, to define the dynamic control procedures of the HVAC apparatus, which allow to vary the outdoor air flow rates in function of the real dilution need of the anaesthetic gas into environment.

The air flow rate variation is achieved by using an algorithm that, through the input data, measures the anesthetic gas concentration levels released into environment during the activity. In order to carry out these experiments, this plant was set up for a function of outdoor air alone, as prescribed by several international laws.

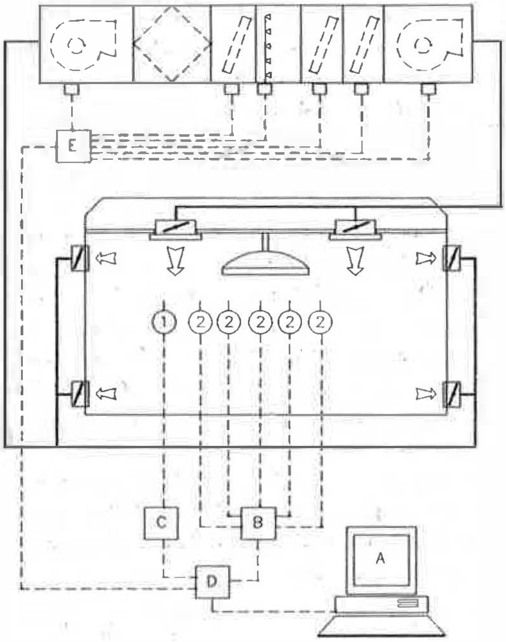

Fig.1 - Scheme of the testing room.
1. dosage point - 2. monitorage probe - A. data acquisition system - B: gas monitoring system - C: gas emission system - D: control unit - E: regulation system.

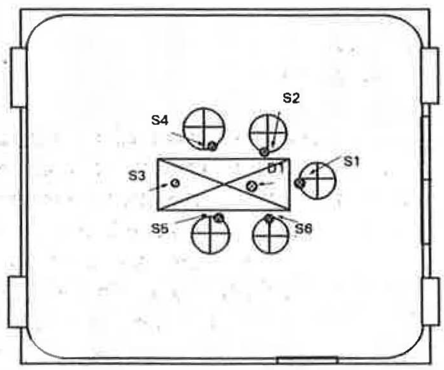

Fig.2 - Dosage points Di and tracer gas monitorage Si, inside the room.

For this reason, the testing room was equipped with an object similar to an operating bed and 5 dummies that represent the usual medical staff working.

In relation to the place where the head of the patient lays on the operating bed, a tracer gas releasing system was placed which controls dosage. We used gas SF6 because it is harmless, non toxic and easy to identify by experimental apparatus.
Thus, using this control system, it is possible to achieve periodical outlets of gas in prearranged quantities and at prefixed time.
Each dummy is equipped with an air exhaust tube, whose diameter was only a few millimeters wide. This tube is placed on the head of the dummy. All tubes are connected to a system which analizes the concentration of the gas used as tracer. In this way, it is possible to monitorize in detail the concentration levels of the gas for every dummy, in function of the HVAC plant typologies adopted and the prearranged dosage.
For the experiments described above, the testing room was equipped with 4 air supply grilles, put on the ceiling, and 8 exctraction air grilles, put on the walls. The last were installed on two opposite walls (Fig.1 and 2).

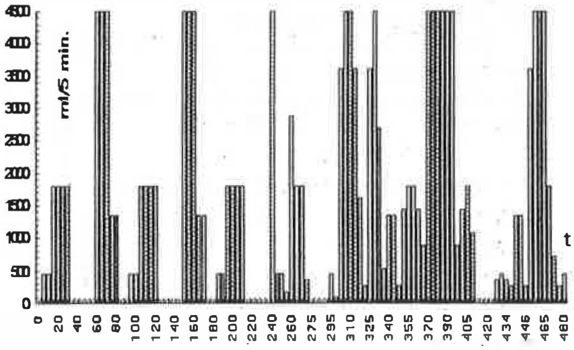

Fig.3 - Dosage period cycle in ml for 5 minutes versus time in minutes

These grilles were equipped with motorized shutters. Thus it was possible to vary: the distribution of supply and exctaction air flow rates, the pressurization level into environment and the turbulence intensity at the zone of the operating bed. The experiments were conducted by inducing the SF6 supply gas cycle into environment, (Fig.3), variable between 2 and 15 ml/s. The last value is very high and not representative of real conditions.
The adopted time interval results very high in confront of the normal values. The fixed cycle has not derived by any reference model, so it is purely ideal. This choice derives from the fact that the rate of the medical gas outlet depends on several variables, not easily representable, rather unknown, such us the kind of operation, the anaesthetic type, the somministration modality of the same, the somministrated gas quantity to the patient, his own metabolism, etc... However, as we are going to demonstrate later on, this hypothesis does not alter the experimentation discussed results.
In order to evaluate the plant efficiency at different ventilation rates, two different tests have been conducted. In the first case, the outdoor air flow rate has been maintained constant and equal to 20 volumes per hour (3000 m^3/h).
In the second test, in the control unit of the HVAC system, an air flow rate variation of the algorithm has been fixed, setting between 10 and 30 *ppm* the concentration range at the zone occupied by the team, with a variable outdoor airflow from a minimum of 10 volumes per hour (1500 m^3/h) to a maximum of 20 volumes per hour (3000 m^3/h).
National laws, for the protosside nitrogen, which is the anasthetic gas of common use, indicate at 50 *ppm*, the reference level to guarantee in the operating theatres during the activity. In other countries, this value is slightly different. Therefore, the value fixed for the experiments is prudent.

OBTAINED RESULTS

The concentrations measured by the probes S1-S5 are illustrated at Fig.4 and 5, as well as the number of the outdoor air changes utilised by the plant.
Since the preliminar steps, it was noticed that the highest gas level could be found in correspondence to the S1 and S2 probes, positioned very closely to the outlet point of the tracer gas and representative of the typically occupied zones by the anaesthetist. This S2 probe seemed to be in the most critical position. In detail, S2 probe was used

as the pilot probe, for tests carried out by the variable air flow rate plant. The analysis of both graphics shows surprising results under different points of view.

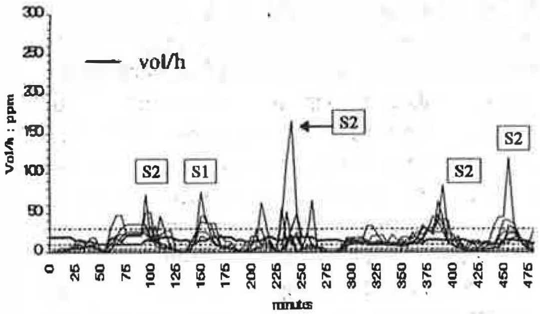

Fig.4 - Probes concentrations inside the room versus time, at variable air flow rates between 10 and 20 volumes per hour.

First, there is a close relationship among the temporal instants, in which the concentration peaks for the two different plants are registered. This is even more obvious by observing Fig.6, in which average concentration values of all probes are illustrated.
Second, there is no close relation between these instants and those at which tracer gas was released.

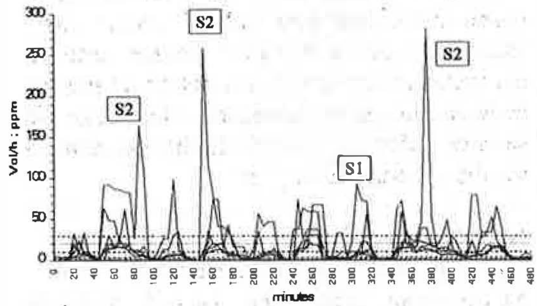

Fig.5 - Probes concentrations inside of the room versus time at constant outdoor air flow rate (20 volumes per hour).

Furthermore, it can be observed that the concentration gas peaks show up indepentally from the plant typology, if they are with a variable flow rate or costant flow rate.

During the second case, the S2 probe registered maximum istantaneous values of concentration between 250 and 300 *ppm*, whereas in the plant at variable airflow, the peaks are not greater than 200 *ppm*..
The average values analysis illustrated at the Table 1, relative to 8 hour time, confirms this observation.

Tabella 1- Tracer gas average concentration at different points of monitorage calculated, for the whole test

Monitoring probes	S1 ppm	S2 ppm	S3 ppm	S4 ppm	S5 ppm	S6 ppm
variable flow rate	18	20.3	11.9	9.6	11.2	14.3
constant flow rate	9.4	37.8	17.5	6.8	8.2	8.5

For the plant at constant air flow rate, the S2 probe measures average values superior to the concentration of 30 *ppm*, taken as reference for carrying out tests. This value is always less than to that one indicated by more international laws. Furthermore, it corresponds to a dosage period at elevated intensity, rarely realized in an operating theatre.
The explanation of these behaviours, apparently abnormal, lies to the fact that the air flow, inside the testing room, is turbulent. In a constant air flow plant, the turbulence intensity assumes always the same characteristics versus time. This causes the presence of preferable ways of air flowing that do not vary during the experimentation.
On the contrary, for a variable air flow plant, turbolence intensity continously varies, thus the air ways change during the time, determing a better gas diluition.
For a variable air flow plant, the graphics analisys of Fig.4 and Fig.7 shows the reaction capacity of the HVAC system to increase and reduce the air flow in function of the concentration measured by the S2 probe.

CONCLUSIONS

The experiments conducted suggest the following considerations:

- for the problem of anaesthetic gases, the use of a high ventilation rate does not guarantee, for itself, a good quality control into environment.
- the use of a variable air flow plant allows a better rimesculation of the air currents and a better washing of the environment.
- in the last case, considerable energy savings are obtained, in order to guarantee an optimal function of the operating theatre in hygienc terms and health prevention of the staff.

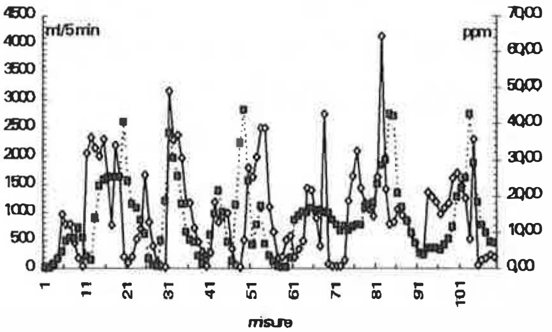

Fig. 6 - Average concentrations calculated for all probes (full-line: plant with constant air flow rate; hatching- line: plant at variable ai rflow rate)

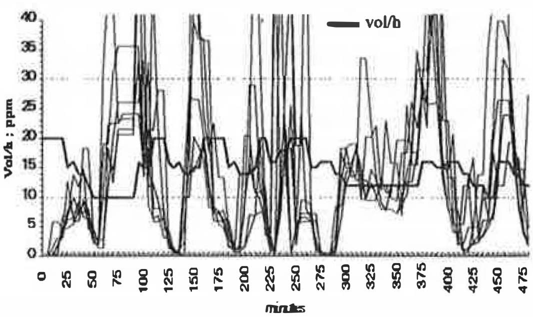

Fig. 7 - Enlarged detail of the Fig.4.

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