Comfort and energy performance of a HVAC system under real conditions for an office block

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Abstract

In the present work, we performed a dynamic simulation of an air-conditioning system for an office block using a mathematical model via Matlab-Simulink. Both the accomplishment of the desired human comfort within the conditioned space and the variation of energy request due to different measurements of volume flow rate have been evaluated, as requested by the European regulation EN 13779 on non-residential buildings. The model has been applied to an office block located in Bologna (Italy), but can also be used for other types of buildings, as well. The HVAC system in the study uses external air supply, with either constant or variable flow rate, and includes three different ways of air treatment: heating and humidification in winter, cooling and dehumidification in summer, and ventilation only, other ways. The study estimated: i) the conditions that can ensure the requested performances at the lowest energetic cost; ii) the energetic gain deriving from the installation of a heat recovery, or/and using carbon dioxide sensors within the conditioned space. The calculation of the energy required has been evaluated in both a typical winter and summer day.

1. Introduction

According to recent regulations on energy saving in buildings, all new structures should guarantee high energy performance [1, 2]. To this aim, the building envelope should be equipped with insulated walls and high efficiency windows. This approach leads to massive thermal insulation, but at the same time, it results in a worsening of indoor air quality, and in hygienic and environmental problems (such as mould growth and airborne diseases). A healthy quality of life imposes a good indoor air quality especially where people spend most of their time [3], so it is mandatory to guarantee adequate air exchanges to reduce indoor pollution to "acceptable" levels. Energy-saving regulations should consider the indoor comfort not only intended as thermo-hygrometric parameters, but also air quality, conditions that are achieved with the emission of fresh and clean air. One solution for non-residential buildings is balanced mechanic ventilation to dilute and extract indoor pollutants. Moreover, using this strategy in an all air conditioning system, the air itself is the carrier to reduce or add thermal load, directly improving indoor comfort condition. The efficiency of this type of air control relies on project decisions, especially on the calculations of external mass flow rate. Actual indoor air quality recommendations enforce high quality standards, which demand high external airflow (in order to remove indoor pollutants) with the consequence of major energy consumption.

The aim of this work was to evaluate both the achievements of desired thermohygrometric requirements of the air-conditioned areas, and the variation of energy requirements according to different evaluations of airflow rate as requested by law for non-residential buildings. For this purpose, a dynamic simulation model of a HVAC system built in Matlab-Simulink, already applied for the evaluation of energy and comfort performance in hospital rooms [4] has been used. We hypothesized that, given the same indoor air quality: i) air-conditioning systems using a variable controlled ventilation ensure a better indoor comfort and air quality as well as a lower energy consumption than those using constant air flow rate, and ii) a CO_2-based demand-controlled ventilation allows higher energy saving than those

calculating airflow rate using a prescriptive approach. To calculate the airflow rate we used the European EN 13779 [5] regulation.

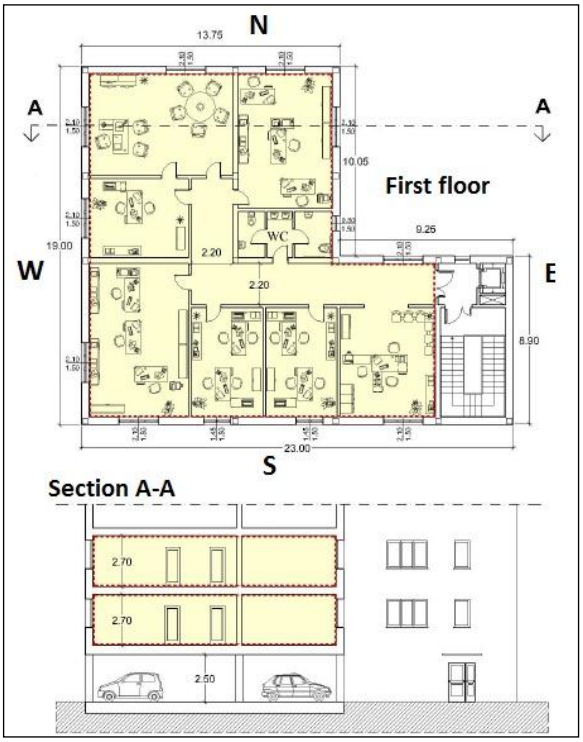

Fig. 1 – The office block

The mathematical model has been applied to a two-floor office of 533 m² floor area and having a volume of 1439 m³, as shown in Figure 1.

2. Description of the model

Air-conditioning systems are required to produce and maintain appropriate thermo-hygrometric conditions in buildings, accordingly to their final use. They ensure adequately comfortable conditions, defined by ASHRAE as satisfactory conditions for indoor environments [6]. Given the rate of metabolic heat production (according to people's physical activity), the major factors acting on thermo-hygrometric comfort are:

- dry air temperature (t);
- relative humidity (UR);
- air velocity.

The best technical solution is given by air conditioning systems which produce and maintain appropriate conditions of temperature, relative humidity, velocity and air cleaning regardless of external air variations. Indoor temperature is maintained at the desired values either adding or removing heat, while the relative humidity control is preserved by air humidification in winter, and air dehumidification in summer.

As shown in Figure 2, the proposed model allows the simulation of an air conditioning system in a dynamic mode, and the analysis of the interaction between the indoor environment and its occupants.

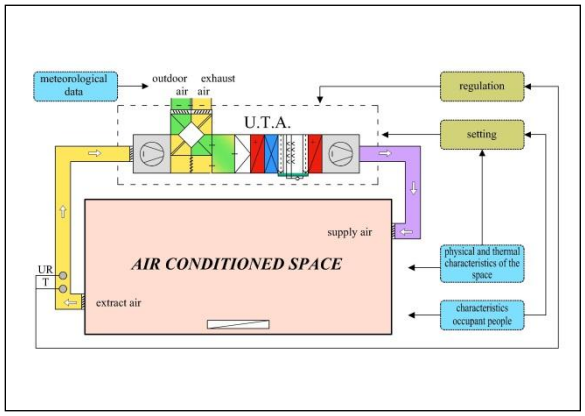

Fig. 2 – Organization of the office block system

To this aim, we used Simulink, a simulation software exploiting Matlab. The built model is characterized by fast calculation, simplicity, and ability to solve differential equations (introducing the temporal variable). It consists of (Figure 3) an:

- air conditioning system;
- air conditioned space.

The air conditioning system is a plant able to produce and maintain the required conditions for indoor comfort. It is modelled by Simulink as an air handling unit acting on equipment, and on constitutive devices.

The air conditioned space is a closed area that can be heated or cooled at specific set-points and can consist of a single room, several rooms on the same or on different floors, or the entire building. Within the Simulink model, the air conditioned space is divided into two parts describing indoor air quality and thermo-hygrometric conditions. Two more components allow the right operation:

- data acquisition;
- calibration and regulation.

During the simulation, data acquisition includes both outdoor and indoor air properties

(temperature, relative humidity, and air quality). The indoor environment is characterized by its dimensions, thermal features such as thermal transmittance, use (internal load), occupancy levels, and occupant characteristics (metabolic rate, carbon dioxide production etc.).

The calibration of the system was performed in a steady-state condition (the data were defined as constant during time); the dynamic condition of the system was obtained using the automatic regulation, to rectify the values previously defined on the modification of the data introduced.

3. filtering section;
4. preheat coil;
5. cooling coil;
6. humidifier;
7. reheat coil;
8. fan.

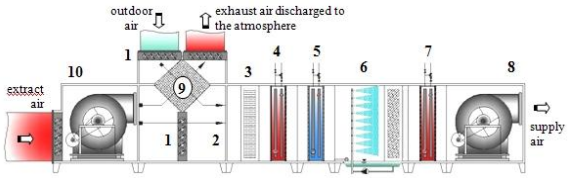

Fig. 4 – The air handling unit

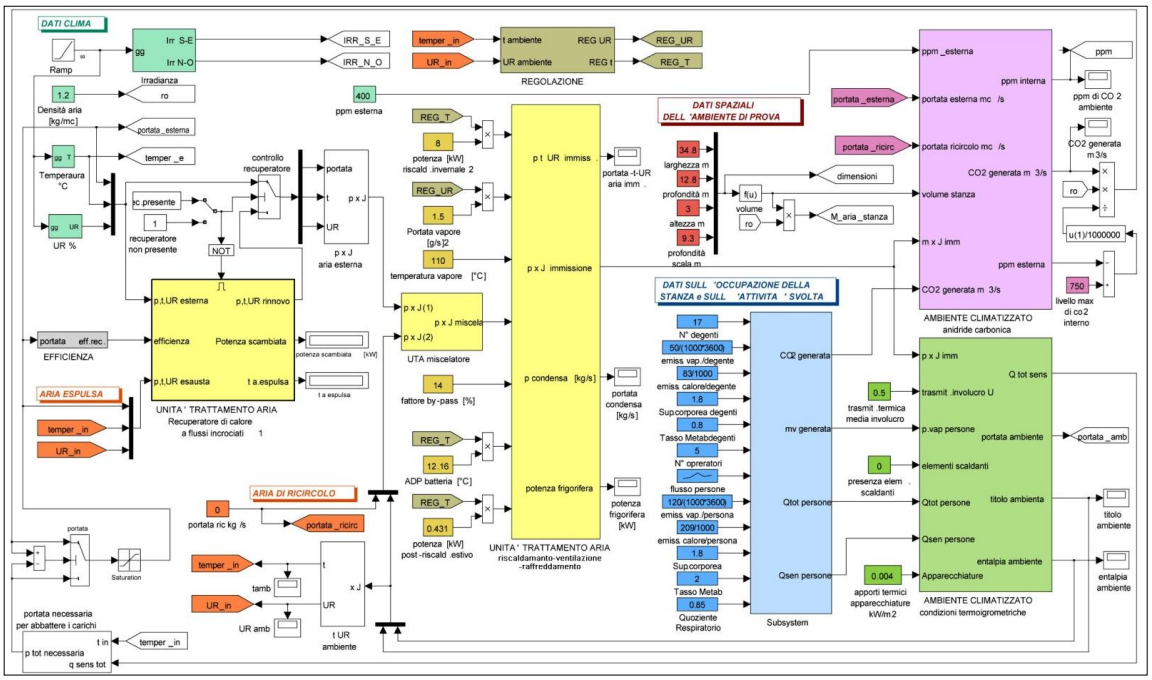

Fig. 3 – Model use for the office block

2.1 The air handling unit

The Air Handling Unit (AHU) consists of all the components of the system which take outdoor air, and filter and treat it to the required thermo-hygrometric indoor inlet characteristics.

Figure 4 shows a typical central system that supplies conditioned air to a single zone. During the process, the air encounters the following components:

1. dampers;
2. air mixers section;

Whenever an energy recovery is needed, the used AHU is equipped with a heat exchanger (9); in this case a second fan (10) is present. The reported application uses an all air conditioning system with water humidification. In the AHU, the air flow depends on external air temperature:

1. In winter time, when $t_e \leq 20$ °C, the air encounters: damper ⇒ heat recovery ⇒ mixing section ⇒ filters ⇒ preheat coil ⇒ humidifier ⇒ reheat coil ⇒ supply fan. Whenever the indoor temperature (produced, for example, by a high number of occupants) can heat the external air to the requested conditions of comfort, the heating

system is not activated, not operating the corresponding coil.

2. In summer time, when $t_e \geq 25$ °C, the air encounters: damper ⇒ heat recovery ⇒ mixing section ⇒ filter ⇒ cooling coil ⇒ reheat coil ⇒ supply fan.
3. In case of t_e intermediate values, no air treatment is needed and the system works only in ventilation mode.

Each component, containing a single air handling unit, operates only in the case of activation, which follows the comparison between t_e values and limit values as defined for the winter or summer regime. It is always possible to know the components which are active, for a better representation of the model and to reduce computational time during simulation.

2.2 Heat recovery system

The heat recovery system (which can be manually switched on or off) can save energy from the ejected air, Figure 5. The model employs a cross flow heat exchanger able to exchange both sensible and latent heat, but unable to exchange humidity since the two air fluxes are kept separate by specific sealing in the plates. Any air infiltration, contaminant gases (polluting materials), biological hazards and particulates are completely blocked.

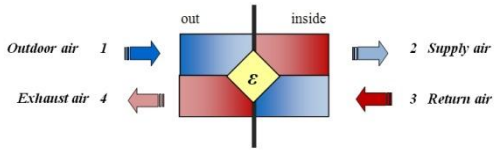

Fig. 5 – Scheme of preheat coil

The heat recovery system is activated only whenever the air is thermally treated. When only ventilation is present, the system is either useless or disadvantageous, since it can worsen indoor comfort, increasing the temperature. The heat flux exchanged (Eq.1) is proportional to the efficiency of the recovery system, to the air flow, and to the difference of the temperature of the fluxes according to the following equation:

$$\dot{Q}_r = \varepsilon \left[\dot{m}_a \, c_p \, (t_3 - t_1)\right] \quad (1)$$

2.3 Air mixers section

In the mixing box, the adiabatic mixing between outdoor air and the indoor air takes place only if the temperature of the outdoor air is uncomfortable.

2.4 Preheat coil

The heating takes place in the preheat coil, where an hot fluid exchanges heat with the flux of the moist air (Figure 6). The characteristics of supply air are obtained by a mass and energy balance of dry air and vapour.

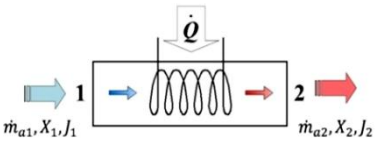

Fig. 6 – Scheme of the preheat coil

2.5 Humidifier

Air humidification is obtained by injecting water inside the air. The conditions of exiting air can be obtained from the mass and energy balance.

2.6 Cooling coil

In the cooling coil, Figure 7, the cooling and dehumidification of the air takes place, to reduce the temperature and the humidity ratio.

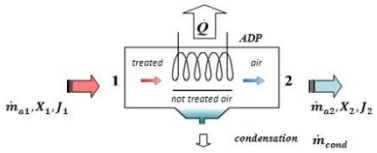

Fig. 7 – Scheme of the cooling coil

The cooling coil is characterized by the "By-pass Factor" (BF) which represents the ratio between not treated and total air flow. In the model a BF = 0.14 has been used.

3. The conditioned space

The conditioned space is a closed environment, with one or more rooms placed also on different floors, or the entire building, heated or cooled at specific temperatures (set-point). In the model, it corresponds to the two floor office block (Figure 1).

The conditioned space has been divided into:

- thermo-hygrometric component;
- CO_2 component.

3.1 Thermo-hygrometric component

The humidity ratio and the enthalpy for this component (Figure 8) is obtained by a mass and energy balance in transient regime (Eq. 2, 3).

$$M \frac{dX_{Amb}(\tau)}{d\tau} = \dot{m}_a X_{imm} + \dot{m}_v - \dot{m}_a X_{Amb}(\tau) \qquad (2)$$

$$M \frac{dJ_{Amb}(\tau)}{d\tau} = \dot{Q}_{tot} + \dot{m}_a J_{imm} - \dot{m}_a J_{Amb}(\tau) \qquad (3)$$

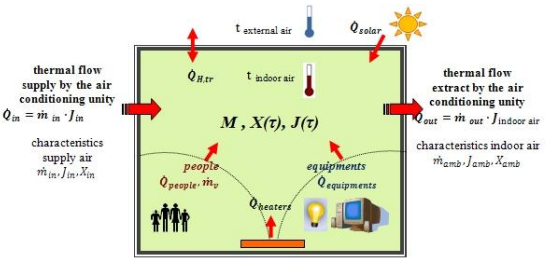

Fig. 8 – Interaction between the conditioned area and outside

3.2 CO_2 component

The study of thermal comfort cannot be separated by indoor air quality. There is a chemical-physical and biological balance between a person and the environment; therefore the air quality control (based on the degree of indoor pollution) is a peculiar part of environmental comfort. The diversity of pollutants potentially present in closed environments, excludes the possibility to identify a general marker of air pollution.

The bio effluents are considered the main responsible agents of indoor pollution [7], and they include gases produced by the body (through respiration and skin) such as CO_2, humidity, aromatic compounds, esters, and alcohols. Their concentration is in general difficult to be measured and limiting values are rarely found, with the exception of CO_2. Indeed, CO_2 concentration is an indicator of anthropic pollution since it is produced with respiration [8]. For the carbon dioxide calculation [9] it is necessary to know the number and the typology of people present each time in the environment. CO_2 produced by each person, Eq.4, is proportional to the oxygen consumed during respiration (VO_2) which is related to body shape, (A_D), sex, age, Respiratory Quote (RQ) and physical activity (M):

$$\dot{G}_p = 0.83\ \dot{V}_{O_2} = 0.83\ \frac{0.00276\ A_D\ M}{(0.23\ RQ + 0.77)} \qquad (4)$$

The variation of indoor carbon dioxide depends on its concentration in the inlet and outlet air, and on its indoor production (scheme on Figure 9) and it is calculated with Eq.4.

$$V \frac{dc_{amb}(\tau)}{d\tau} = \left(\dot{G} + \dot{Q}_v\ c_{imm}\right) - \dot{Q}_v\ c_{amb}(\tau) \qquad (5)$$

The concentration of CO_2 in the supply air depends on the typology of air composing the flux (in the general case, there is both external and recirculated air). As an initial condition we used CO_2 concentration as obtained at 00.00 (midnight) of the day preceding the day of the simulation.

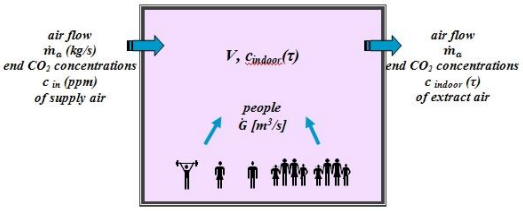

Fig. 9 – Correlation between indoor air quality and occupants

4. Calculation of the air flow and results of the simulations

The simulation of the office block was performed on two typical days in Bologna - Italy: one in winter time (January 17th), when the heating system is active the entire working day; and one in summer time (July 17th), when the cooling system works only during daylight hours when t_e>25°C, while in the remaining hours it only works as ventilation.

The system is supposed to maintain the following hygrometric parameters [10]:

Winter	t = 20°C	UR = 50%
Summer	t = 26°C	UR = 50%

and the internal air quality accomplishes IDA2 as defined by regulation [4].

Regarding the constructive characteristics, the thermal transmittance of the envelope was considered uniform and equal to 0.5 W/(m² K).

All the employees and the visitors are characterised by a metabolic rate of 1.2 met and with a vapour and heat emission per person evaluated as 50 g/h and 126 W. The working time is from 9 a.m. to 7 p.m. The outdoor concentration of CO_2 is of 400 ppm, whilst for the outside temperature the Arpa hourly data was used in the form of a sinusoidal function.

The calculation of the external airflow has been done according to the EN 13779. For each calculation methodology, the fulfilment of the thermo-hygrometric requirements (for indoor air conditioned environment) was verified. It was possible to calculate the energy required by the systems instantaneously and during the entire simulation, as well as the instantaneous concentration of CO_2 for the evaluation of indoor air quality (Fig.10) [5].

Category	Description	CO2-LEVEL ABOVE LEVEL OF OUTDOOR AIR IN PPM	
		Typical range	Default value
IDA 1	High indoor air quality	≤ 400	350
IDA 2	Medium indoor air quality	400-600	500
IDA 3	Moderate indoor air quality	600-1000	800
IDA 4	Low indoor air quality	>1000	1200

Fig. 10 – Acceptable CO2 concentration [5].

EN 13779 regulation allows to calculate the load both using the *prescriptive* and the *performance* related method.

1. The *prescriptive approach* defines the minimal air loading per person according to the final use of the building. In the case of offices it requires a minimal volumetric flow rate of 12.5 $l \cdot s^{-1}$ per person (IDA2):

1.1. In the systems with constant air volume, the air flow per person is multiplied by the expected presence of employees and visitors in the office block (i.e. 50 people according to the dimension of the office and the EN 13779). From the simulations it is possible to obtain instantaneous values of the coil heat flux, with or without the insertion of the heat recovery as shown in figures 11 and 12.

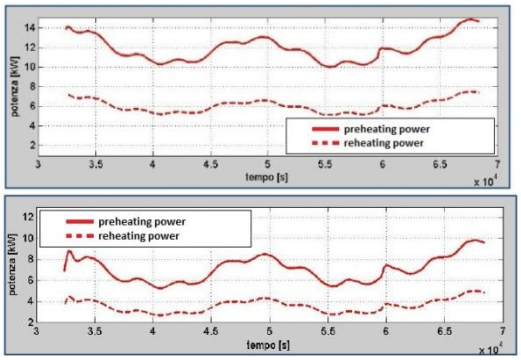

Fig. 11 – Coils power in a winter day (Jan 17th) without (a) and with (b) the heat recovery

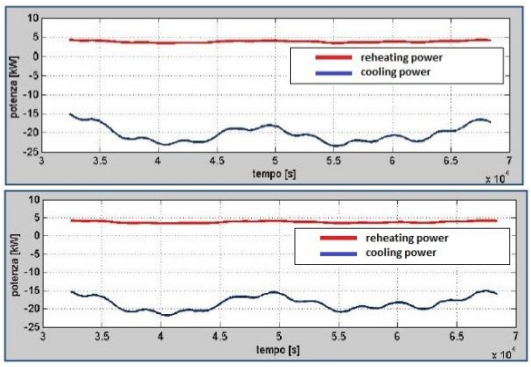

Fig. 12 – Coils power in a summer day (Jul 17th) without (a) and with (b) the heat recovery

Figure 13 shows carbon dioxide concentration produced by 50 people at 1.2 met. The simulation indicates *high* air quality classification always below the upper limit of IDA1.

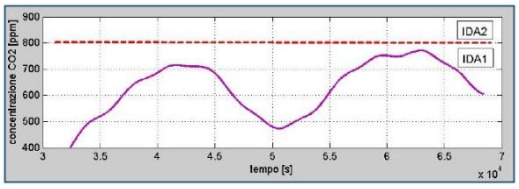

Fig. 13 – CO2 concentration (50 people)

Given the indoor air classes of the regulation EN 13779 for offices (IDA2), the number of people has been reduced to the value of 30. In Figure 14 the indoor air quality results below the limit of IDA2.

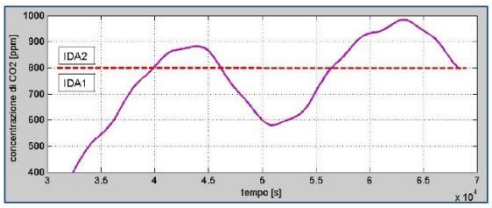

Fig. 14 – CO_2 concentration (30 people)

1.2. In the systems with Variable Air Volume (VAV), the air flow per person loading is multiplied by the number of people detected by specific sensors placed at the entrances of the office block. In Figure 15 the human occupancy profile for the entire office from 9 a.m. to 7 p.m is shown.

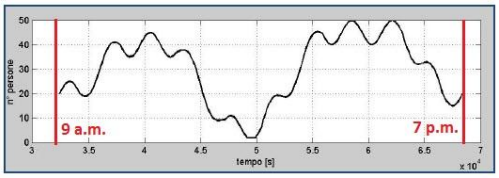

Fig. 15 – Office people occupancy

Fig. 16 – External mass flow rate

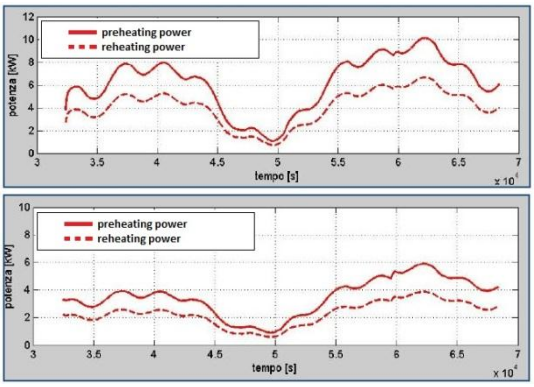

Fig. 17 – Coils power in a winter day (Jan 17th) without (a) and with (b) the heat recovery

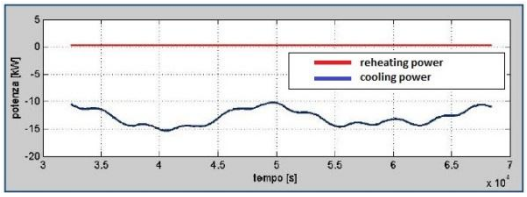

Fig. 18 – Coils power in a summer day (Jul 17th) with heat recovery

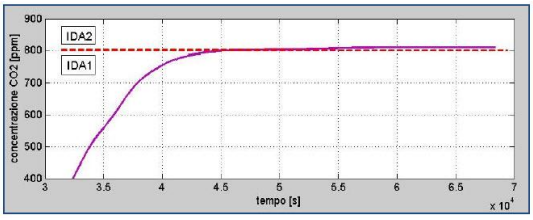

Fig. 19 – CO_2 concentration (VAV)

Using the people occupancy the mass flow rate is calculated multiplying the instantaneous value by flow rate of 12.5 $l \cdot s^{-1}$. The profile is reported in Figure 16.

The results of the simulation of the coil heat flux in the winter and summer days are reported in figures 17 and 18.

Carbon dioxide concentration is reported in Figure 19 for the simulation of an all air system with the variable air volume using the profile of Figure 16. Also in this condition the indoor air quality is *high* (IDA1 classification) except for almost four hours in the late afternoon in which indoor air quality is *medium* (IDA2).

2. The *performance related approach* defines the limits for CO_2 concentration and allows the calculation of outdoor air loading which ensures the limits in two different ways:

2.1. The first identifies the quantity of CO_2 produced by a "typical" occupant, and this value is multiplied by the number of people instantaneously detected by an automatic counting sensor. External air flow (Figure 20) is calculated to maintain indoor CO_2 concentration below the default value of 500 ppm above the level of the outdoor concentration (400 ppm).

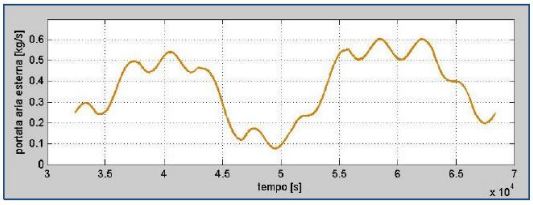

Fig. 20 – External mass flow rate

Heat flux and CO_2 concentrations obtained by the simulation are shown in figures 21 and 22.

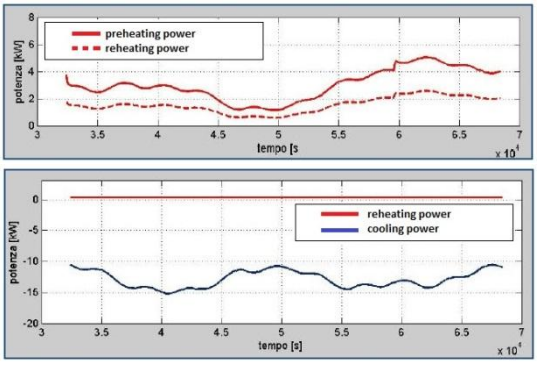

Fig. 21 – Coils power in a winter (a) (Jan 17th) and summer (b) day (Jul 17th) with heat recovery

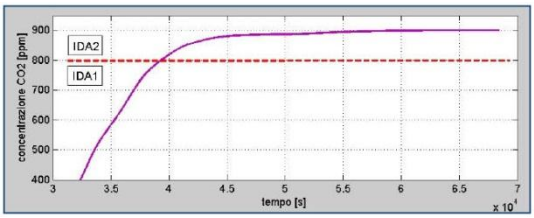

Fig. 22 – CO_2 concentration

2.2. The second way detects the carbon dioxide concentration using an indoor CO_2 sensor. This measured value is compared with the default one, 500 ppm above the outdoor concentration, corresponding to IDA 2 air category (Figure 10), and the range of ±100 ppm is used by a proportional-integral regulator to determine the instantaneous external mass flow rate. Whenever the mass flow rate is below 0.24 $kg \cdot s^{-1}$ (that corresponds to 0.5 volume per hour exchange of indoor air) this value is set to 0.24 $kg \cdot s^{-1}$. Figure 23 shows the profile of the external mass flow rate.

Fig. 23 – External mass flow rate

Heat flux and CO_2 concentrations obtained by the simulation are shown in figures 24 and 25.

The energy requirements for each approach during the representative winter (January 17th) or summer (July 17th) days are reported in tables 1 and 2.

The *prescriptive approach* allows both a constant and variable air flow rate. EN 13779 regulation specifies IDA2 air quality for office use and provides: i) typical value for human occupancy in terms of floor area per person based on the kind of building use; ii) the rate of outdoor air per person. In constant air flow systems the calculated values lead to a *high* air quality (IDA1). The reason is related to an overestimated number of people for the office object of this study. In the studied case the IDA2 air quality is reached with an occupancy of 30 people, that corresponds to 1 person each 18 m^2, instead of the 50 occupants given by the regulation.

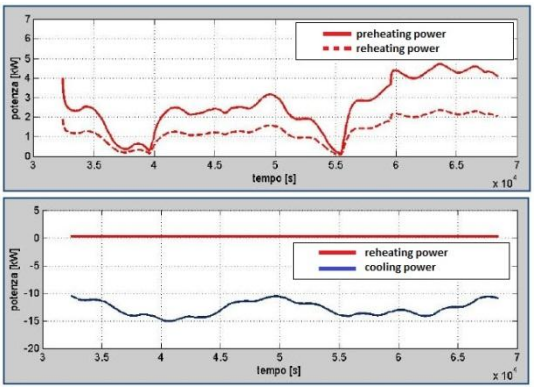

Fig. 24 – Coils power in a winter (a) (Jan 17th) and summer (b) day (Jul 17th) with heat recovery

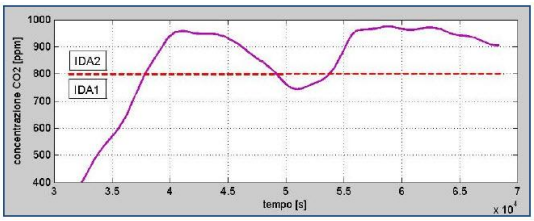

Figure 25 – CO_2 concentration

Category of indoor air reached:	IDA 1		IDA 2	
Outdoor air flow rate - calculation way:	without Heat Recovery	with Heat Recovery	without Heat Recovery	with Heat Recovery
Prescriptive approch				
Constant ventilation air flow (50 people)	179	106		
Constant ventilation air flow (30 people)			102	57
Variable air flow (Rate of outdoor air per person) with counting sensors			102	58
Performance related approach				
Variable air flow (Rate of outdoor air by CO_2 level) with counting sensors			82	45
Variable air flow (Rate of outdoor air by CO_2 level) with CO_2 sensors			72	39

Table 1 – Energetic requirements - simulation on January 17th [kWh]

Category of indoor air reached:	IDA 1		IDA 2	
Outdoor air flow rate - calculation way:	without Heat Recovery	with Heat Recovery	without Heat Recovery	with Heat Recovery
Prescriptive approch				
Constant ventilation air flow (50 people)	241	224		
Constant ventilation air flow (30 people)			216	205
Variable air flow (Rate of outdoor air per person) with counting sensors			144	132
Performance related approach				
Variable air flow (Rate of outdoor air by CO_2 level) with counting sensors			141	132
Variable air flow (Rate of outdoor air by CO_2 level) with CO_2 sensors			140	131

Table 2 – Energetic requirements - simulation on July 17th [kWh]

In the prescriptive approach the variable air flow rate is more reliable; the IDA2 air quality is always achieved. Notably, the default value of 12.5 $l \cdot s^{-1}$ recommended in the EN13779, as the rate of outdoor air per person, seems lightly overestimated for the office object of the present

study. It results in a CO_2 concentration that is either in the IDA1 range (in the morning), or in the lowest IDA2 range values.

The two *performance related approaches* always reach the required IDA2 air quality, since the calculated carbon dioxide level is used to compute the mass flow rate. To this aim, the proposed model is essential to calculate and adjust the outdoor airflow rate.

In order to achieve IDA2 air quality both i) *prescriptive* and *performance related approaches,* and ii) constant and variable air flow rate are suitable. The difference between the two approaches is evident in the consumption of energy. The employing of *performance* methods based on the CO_2 produced in the indoor environment is energetically more convenient than using prescriptive methods, especially in winter. Moreover the addition in the air handling unit of the heat recovery section reduces energy consumption in particular in winter.

5. Conclusion

From the results obtained by the numerical simulations, it is possible to conclude that:

- In order to achieve IDA2 air quality all the described methods are suitable;
- Variable volume systems are able to adjust to effective occupational loading and represent the best solution. Performance related methods based on the indoor pollution as the major input (evaluated as CO_2 produced by occupants), are more efficient since they always fulfil indoor standards of air quality with minor energy consumption.

6. Nomenclature

$\dot{G}_p$	Carbon dioxide production (per person)	m^3/s
J	Specific enthalpy of moist air	kJ/kg_{as}
M	Total mass of air	kg
M	Rate of metabolic heat production	met
$\dot{Q}$	Heat flow rate	W
V	Total volume of air	m^3
X	Humidity ratio	kg_v/kg_{as}
c	Carbon dioxide concentration	ppm
c_p	Specific heat	kJ/kg K
h_v	Specific enthalpy of water vapor	kJ/kg_v
$\dot{m}_a$	Mass flow of dry air	kg_{as}/s
$\dot{m}_v$	Mass flow of water vapor	kg/s
t	Temperature of moist air	°C
t_e	Outdoor temperature	°C
t_i	Indoor design temperature	°C
$\mathcal{M}$	Total mass of air in the air conditioned space	kg
ε	Heat recovery efficiency	-
τ	time	s

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