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A new air handling unit system for residential buildings: experiment and simulation-based analysis

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A new air handling unit system for residential buildings: experiment and simulation-based analysis

Emanuele Lazzarini[1,2], Angelo Zarrella[1,*], Giuseppe Emmi[1], Enrico Biasin[2]

[1] Department of Industrial Engineering-DII, University of Padova, Padova, Italy
[2] Aertesi Srl, Conselve, Padova, Italy
[*] angelo.zarrella@unipd.it

Abstract. Energy saving in buildings is one of the main priorities of the last years. To reach this goal, the optimization of the building envelope and plant-systems with high energy performance are necessary. This work looks at the use of the air-handling unit based systems for heating and cooling of residential dwellings characterized by high thermal insulation level. A plant system based on a new concept of air-handling unit is analyzed by means of experimental analysis carried out in a real common apartment, named DemoLab and realised near Padova (Italy). This system provides both the heating and cooling thermal loads. The research outlines the analysis of the test measurements carried out in the laboratory, focusing on the profiles of air temperature, humidity and CO_2 rate in several points and different rooms. As result, the analysis verified the control strategy implemented in the investigated plant system to improve the indoor environmental quality inside the building. Finally, the new system was also analysed in different climatic conditions by means of transient computer simulations implementing the current control strategies.

1. Introduction

Efforts to reduce carbon emissions have become an important challenge of the last decades. Residential buildings account for about 27% of global final energy consumption and about 17% of global carbon emissions [1]. In Europe, the Energy Performance of Buildings Directive (EPBD) [2, 3] and the Energy Efficiency Directive (EED) [4] looks at improving of the energy efficiency in buildings. The current tendency for new constructions is to plan low or nearly zero energy buildings (NZEBs). The EPBD outlines that all the new buildings must be NZEBs by the end of 2020. However, the retrofitting of the existing buildings represents the greatest challenge as it can provide a high potential of reducing energy consumption improving the quality of buildings' envelopes or using energy-efficient heating and cooling technologies. Another important issue regards the quality of the indoor environment. Ventilation to remove the indoor air involves a thermally comfortable indoor environment; an insufficient ventilation rate is associated with health problems such as inflammation, respiratory infections, asthma, allergies and sick building syndrome [5]. In this context, mechanical ventilation systems offers several advantages but it consumes energy and can be noisy.

D'Este et al. [6] investigated different systems for the improvement of the thermal efficiency related to the ventilation rate of the buildings. They studied a direct heat recovery from the exhaust air and an indirect recovery by the use of a heat pump and a combined solution of the first two, by means of computer simulations. They concluded that the best solution was the heat recovery coupled with the heat pump. Nowadays the building envelope, especially in new constructions, is very airtightness and, for this reason, the use of mechanical ventilation units in buildings is mandatory to guarantee the air change rate [7] and the indoor environmental quality.

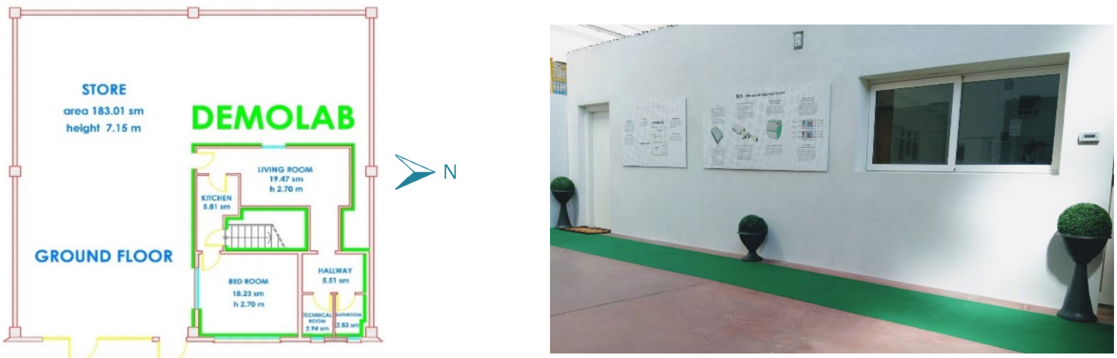
This work investigates a mechanical ventilation system, called EoS, for residential buildings with low energy consumption. This system is able to satisfy the heating and cooling demand of the residential building without other auxiliary device, consequently one only air conditioning system will be installed with economic and management advantages for the user. The necessary condition for the consideration of this system is that the building envelope presents high quality in order to decrease both the heating and cooling demand. To investigate the energy behaviour and the real operating conditions of this new system, the laboratory DemoLab was built. Finally, EoS energy performance is evaluated via transient computer simulations taking into account the weather, the heat gains, the building envelope.

2. Method

Energy saving in buildings depends on both the energy efficiency of the air-conditioning system and the thermal performance of the envelope. To this purpose, the perimeter walls of the laboratory DemoLab were thermally insulated in order to replace a high energy performance building. At the second step, a measurement and acquisition system was designed and installed in order to evaluate the thermal behavior of DemoLab measuring air temperature, relative humidity, CO_2 level and air velocity in each room. In addition, in order to evaluate the energy performance of the air-handling unit system, also the electrical and thermal energy consumption of the system was measured. All measurements are collected and stored via an acquisition system that provides to print and plot the values. The status of the real time situation can be seen in a web frame that replaces the layout of DemoLab.

2.1. Experimental setup

DemoLab (Figure 1) represents a small apartment of about 55 m^2 with a living room, a kitchen, a bedroom, a bathroom, and a technical room. It is realized inside a shed of floor area equal to about 183 m^2. The pre-existing brick walls were used and a new plasterboard was added to make a structure that reflected a common small apartment. On the East side, three windows are present, consequently the contribution of beam and diffuse solar radiation is considered. Other windows are present in the living room and bedroom exposed on the shed: in this case, part of the diffuse solar radiation from the skylight of the building enters; this is equivalent to the presence of a shading system. In the future, suitable lamps will be used to simulate the contribution of solar radiation on this side.



(a) (b)

Figure 1. DemoLab: (a) layout, (b) real status.

The perimeter walls consist of three layers: an insulation layer made of rock wool with thickness of 120 mm is placed between two panels of 20 mm plasterboard. Table 1 outlines the thermal properties of the materials that were used. At the end, the thermal transmittance of the perimeter wall was equal to 0.27 W/(m^2 K).

The core of the system is surely the EoS air-handling unit whose characteristics are reported in Table 2. The system is equipped with a heat recovery unit that allows it to extract part of the thermal energy from the exhaust air in order to increase the energy efficiency of the machine. EoS system also contains the typical air-water finned heat exchanger where flows the hot or cold water produced by a heat pump according to the operating mode. One of the main functions of EoS system is to provide the air renewal, which is done by schedule and when the relative humidity and/or CO_2 values in the zone do not satisfy the comfort conditions; this control is automatically switched on when the air quality inside the room is not within the ranges to obtain thermal comfort conditions inside the room.

Table 1. Thermal properties of envelope materials.

	Unit	Plasterboard	Rock wool
Thermal conductivity	[W/(m K)]	0.25	0.035
Density	[kg/m^3]	760	120
Specific thermal capacity	[J/(kg K)]	1000	1030

Table 2. Characteristics of EoS air-handling unit.

	Unit	Value
Total cooling thermal capacity	[kW]	3.2
Sensible cooling thermal capacity	[kW]	2.4
Heating thermal capacity	[kW]	4
Water volume flow rate	[L/h]	550
Energy efficiency of the heat recovery in heating mode	[-]	90
Energy efficiency of the heat recovery in cooling mode	[-]	85
Nominal external air volume flow rate	[m^3/h]	200
Nominal air volume flow rate (renewal + recirculation)	[m^3/h]	500

Figure 2 shows the operating modes of EoS in the general case when both recirculated air from the zone and renewal by external air are switched on. The exhaust air is passed through the cross-flow recuperator in which it exchanges heat with the renewal air taken from outside. Before being released into the room, the air is heated or cooled by the air-water finned heat exchanger. The system controls the air temperature, relative humidity and CO_2 level. The only one of the three parameters that is bi-zone type in DemoLab is the air temperature, having been installed two thermostats, respectively in the bedroom and living room; on the other hand, sensors in the living room control the relative humidity and CO_2 values. As regards the relative humidity and CO_2 control, which occurs autonomously with respect to air temperature, if the set point condition is not respected, the bi-zone damper and the fans are switched on. If the recirculation mode is switched on, fans run at the minimum speed so as not to affect the level of thermal comfort. EoS system is coupled to an air-to-water heat pump whose characteristics are reported in Table 3.

(a) (b)

Figure 2. EoS air-handling unit: (a) the system with electronic multi-zone damper and plenum, (b) operation when recirculation with renewal is set.

Table 3. Characteristics of the air-to-water heat pump.

	Unit	Value
Cooling thermal capacity *	[kW]	5.8
Heating thermal capacity **	[kW]	6.5
Energy efficiency in cooling (EER) *	[-]	3.05
Energy efficiency in heating (COP) **	[-]	3.09

*External air temperature = 35°C, inlet/outlet water temperature = 12/7°C
**External air temperature = 6°C, inlet/outlet water temperature = 40/45°C

2.2. Test on operating modes

From August 2018 to March 2019, several tests were carried out with different operating modes of the air-handling unit EoS, in order to check the operating conditions and control system of the machine. During these tests, the presence of people inside the apartment was not considered; in the future, the laboratory will be equipped with devices to simulate their presence.

In the experiment here outlined, the CO_2 level was intentionally increased (Figure 3) to simulate the presence of people or other sources. A substantial CO_2 load was added, first in the living room and, after 5 minutes, the same amount was also poured into the bedroom; consequently EoS has turned on its renewal and, although the control on CO_2 is mono-zone, it is sufficient to regulate its entire presence throughout the apartment; in fact, the return time to the set point value (400 ppm) takes place in just 2 hours and 30 minutes, against the 7 hours of the case with renewal turned off.

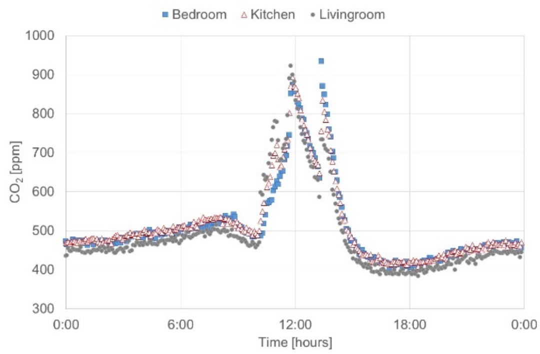


Figure 3. CO_2 profile in the bedroom, kitchen and living room.

3. Simulation results and discussion

3.1. TRNSYS model

Starting from the thermo-physical parameters, from the structure of the dwelling, from its exposure to solar radiation and from its geographical position, a dynamic model of DemoLab was developed in TRNSYS18 simulation environment [8].

The simulations were carried out with internal heat loads in order to consider lighting, appliances and presence of people with a daily scheduling in line with the use of the building. To this end it was considered that DemoLab was occupied by two persons and an average heat load equal to 2.8 W/m^2, due to household appliances is present. As for lighting, led lights with a medium emission of 5 W/m^2 were considered. Particular attention has been paid to the internal vapour sources: in the bathroom, due to the presence of the shower and the washing machine, its emission was equal to 400 g/day, in the kitchen was 4 kg/day.

The entire building plant system was simulated in TRNSYS making use of a Microsoft Excel sheet where the operating conditions of the EoS system were calculated via a procedure developed in Visual Basic programming language. Hourly computer simulations were carried out along two years in order to avoid the effect of the initial conditions. Figure 4 shows the layout of the main program in TRNSYS environment: on the left the input files are inserted, that are the climatic values, the mass flows entered by the EoS system and the respective inlet temperatures, the internal thermal loads. At the centre of the layout is the DemoLab model, including all the thermal and structural features of the building envelope, solved via the Type 56. Starting the simulation, the thermal flows that EoS must provide in heating and cooling are calculated, considering the current control strategies of the system. As result, hourly annual temperature profile is found within each zone as well as the energy consumption of the heat pump coupled to the EoS system. The simulations were carried out using the weather data of two locations: Milan and Rome [9].

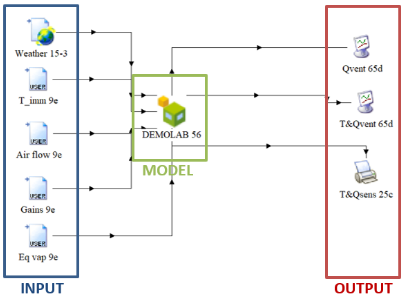
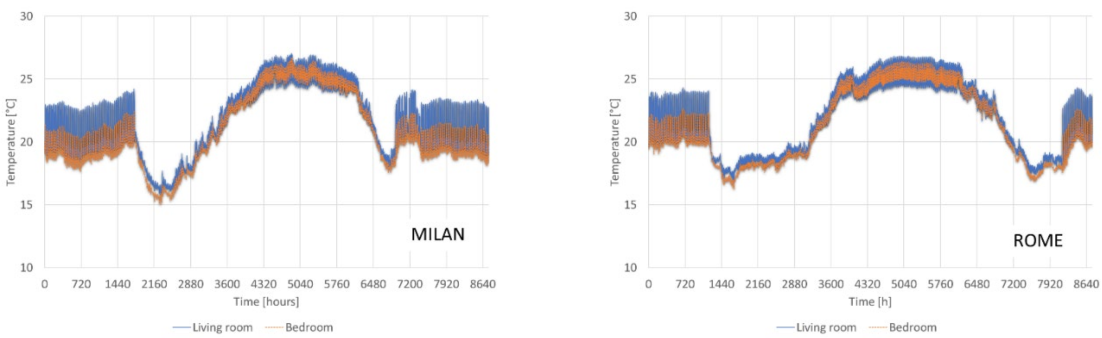


Figure 4. TRNSYS - Simulation Studio plugin layout

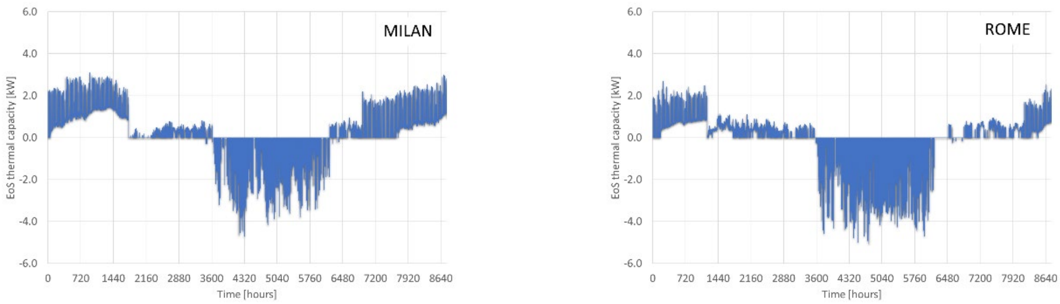
3.2. Results

Figure 5 shows the main results of the computer simulations. In detail, the air temperature in the two thermal zones (i.e., living room and bedroom) is outlined for both Milan and Rome. As it can be seen, in the heating period the air temperature (especially in the living room) is higher than 20°C due to the current control strategy that has as priority the air renewal in the thermal zone. During the cooling season the set point is controlled within a limited band.

Thermal load that EoS (i.e. heat recovery and air-water finned heat exchanger) provides in heating and cooling respectively according to TRNSYS calculations is also shown. As it can be seen, the heating load is low due to good insulation level of the building envelope. The heat recovery allows an energy saving of about 20% in Milan and about 40% in Rome in heating operation whereas its contribution in cooling period is negligible. The cooling thermal capacity is quite similar in both Milan and Rome due to the latent contribution. According to the values from manufacturer of the air-to-water heat pump, also the seasonal energy efficiency (SCOP in heating, SEER in cooling) was calculated making use of the external air temperature of the considered locations. In winter time, the SCOP values were 2.9 and 3.2 in Milan and Rome respectively; in summer, high SEER values were found (4.4. in Milan and 4.5 in Rome) since the machine was switched on when the external air temperature was relatively low (in the morning and evening).



(a) (b)



(c) (d)

Figure 5. Indoor air temperatures and thermal capacity provided by EoS system to the dwelling.

4. Conclusions

In this work, a system based on a small air handling unit, to perform all the functions of air conditioning, air renewal, heat recovery, dehumidification and free-cooling for each room served was investigated. The analysis was carried out using a real small apartment used as laboratory. The experimental tests showed a good capacity of the machine to converge to the relative humidity and CO_2 set point values. Computer simulations in two climatic zones outlined that if the heat gains are controlled this system is able to control the temperature inside the building. The current control strategies have to be improved, especially during the heating operation. These aspects will be investigated in future studies.

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