One-year operation performance of a decentralised all-air HVAC system for a school room

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Abstract. Since the first COVID outbreak in 2020, schools have been considered a substantial issue with regard to the spread of the disease, as they represent indoor environments that are continuously occupied most of the time. Several studies have underscored the crucial role of mechanical ventilation systems in the fight against any pandemic caused by airborne pathogens. AiCARR, through its associated companies, donated a mechanical ventilation system to a public school in Rho, Milan province (IT). The primary objective of the installation was to enhance safety by diluting indoor contaminants, improving indoor air quality, and ensuring thermal comfort. During the course of the project, the focus included advancing energy efficiency and reducing operational and maintenance costs. This article presents the first year operational data recorded by the monitoring system that include outdoor and indoor air temperature, relative humidity, CO₂ concentration and unit electric consumption.

1 Introduction

To mitigate the airborne diffusion of COVID-19 in buildings, the World Health Organisation recommended ensuring adequate ventilation and increasing total airflow supply [1, 2]. The well-known Wells-Riley model is often used to quantify the effect of ventilation air flow on the risk of contagion in indoor environments [3, 4]. For example, Cavallini et al. [5] evaluated the risk of infection in several HVAC system layouts, taking into account the role of air renewal (ventilation) and recirculation in reducing the infection risk due to virus removal or inactivation.

In another study [6], a newly developed CONTAM-quanta approach for infection risk assessment was applied to evaluate the effectiveness of different mechanical ventilation systems in five different buildings (i.e., medium office, large office, small hotel, standalone retail and secondary school).

Among the different buildings, schools in Europe have suffered very long closing periods during the COVID-19 pandemic and the following lockdown periods in 2020 and 2021 [7]. As they are among the most densely occupied environments with continuous occupation, in recent years many studies focused on demonstrating the correlation between increased ventilation and

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reduced risk of contagion [8-10]. Their reopening after lockdown periods has drawn immediate attention to health and safety conditions [11].

Many strategies can be adopted on this issue to reduce infection risk by diluting viral charges [12]: external air infiltration from poor air tightness of the building envelope or aeration from open windows, both due to the temperature/pressure difference between indoor and outdoor environment, or the use of mechanical ventilation systems. The latter is the most effective technique, as infiltration and aeration do not control the internal air distribution and may cause uncomfortable conditions [13]. Additionally, they increase the net energy demand of the building with no chance of heat recovery. In this regard, Korsavi et al. [14] provided a comprehensive analysis of the predictors that influence operations on windows and external doors and their impact on indoor quality, comfort, and energy. Another study reported on the results of indoor environmental measurement for schools in Japan in a cold climate area, considering CO2 concentration, thermal sensation (i.e., students’ feeling of being hot or cold), and a comparison of energy consumption before and after the spread of COVID-19 infection [15]. In another work, Franceschini and Neves [16] addressed the knowledge gap on the modelling of occupant behaviour for naturally ventilated and mixed-mode school buildings. Rodriguez-Vidal et al. [17] investigated indoor comfort in classrooms comparing partial, constant and natural ventilation (like was done during the COVID-19 pandemic) and mechanical and hybrid ventilation in the climate of the Basque Country, Spain. They found that the hybrid system maintained acceptable indoor air quality that also allowed for improved energy efficiency compared to the natural ventilation system.

Pistochini et al. [18] simulated a classroom by EnergyPlus in 13 cities across the US to understand the trade-offs between infection probability and energy consumption of outdoor air ventilation rates and filtration methods. Recently, Busato and Cavallini [19] highlighted that windows opening is not effective in controlling the spread of the disease and that mechanical ventilation can reduce the risk of individual infection by a factor of 3 for the same amount of thermal energy needed, even outperforming the effect of masks.

As already demonstrated, mechanical ventilation systems can result in increased energy consumption due to the fans [20]. Heat recovery, even beyond the simple requirement of the law, may be a viable solution to reduce such energy consumption [21]. Due to their increasing use, reversible air-to-air heat pump systems (that is, a/a heat pump/air conditioner, HP/AC) can be considered a suitable solution for mechanical ventilation in schools. They can be installed downstream of the heat recovery heat exchanger (i.e., thermodynamic recovery) or used alone, without the heat exchanger. This configuration simplifies the system and reduces its initial costs. As a drawback, it allows a lower heat recovery, but this is partially balanced by an increase in the heat pump performance. In fact, the more favourable temperatures at the evaporator and condenser allow a higher coefficient of performance (COP) [22].

Noro and Zilio [23] in a previous study compared different systems (sensible or total heat recovery, heat pump, heat pump coupled to a recuperator) by dynamic simulation, demonstrating that they allow significant non-renewable primary energy savings. Energy analysis highlighted that thermodynamic heat recovery, that is, coupled use of sensible or total heat recovery and reversible heat pump, is the most advantageous configuration for school ventilation both in colder and humid climates like Milan and in milder climates like Palermo, even more when increasing ventilation flow rate (as desirable in the COVID-19 pandemic) and for new or retrofitted buildings. Despite this, the economic analysis revealed that the use of the HP/AC configuration is more advantageous.

Based on these considerations and on previous seminars on indoor air quality, during the COVID-19 period, the Italian Association for air conditioning, ventilation, heating, and refrigeration (AiCARR) promoted a cultural-educational activity to contribute to the training of young technicians in the field of installation of heating, ventilation, and air conditioning plants.
(HVAC). The activity consisted of the design and implementation of an all-air ducted air conditioning and ventilation system to supply a technical laboratory of a professional high school located in the northwest of Italy.

The object of this paper is to describe the installation and the results of the first year of operation (April 1st 2022 – February 12th 2023) in terms of indoor air quality, thermal comfort and energy performance.

2 METHODS

In this section, a brief description of AiCARR’s mission and the project motivations are reported.

2.1 AiCARR’s mission

Founded in 1960, AiCARR has always dealt with issues relating to the responsible use of energy and natural resources and the innovation of energy infrastructures, both in residential and industrial buildings. AiCARR’s members (actually more than 2200) are planners, machinery builders, installers, maintenance operators, scholars, researchers, students, government and national and international organisations.

AiCARR operates with the main aims of producing and disseminating the culture of sustainable comfort, training, and professional development of employees in the field, contributing to the development of legislation for the HVAC sector also by cooperation with other organisations and governing bodies, both Italian and European.

The operation is realised by means of Committees, chaired by Executive Board Members: they coordinate the different activities in which the Association is involved, from the organisation of conferences and seminars to the arrangement of Technical Working Groups, from the planning of training programmes to the publication of articles, from the management of national and international relations to the making public announcements, without disregarding the operation of legislation in the UNI, CTI, and CEN and those directly related to energy efficiency.

Within AiCARR’s mission activities, in 2021, during the COVID-19 pandemic, the Executive Board members had a new idea: involving some of the industrial and planner members along with young scholars from a higher education institute to design and install an air conditioning and ventilation system to serve one of the school’s rooms. The primary motivation behind this project was to foster collaboration among professionals, students, and manufacturers in creating a practical and beneficial system that would serve their own school.

2.2 Description of the ventilation system

The air conditioning and ventilation system was implemented at the ‘Puecher-Olivetti’ Higher Education Institute, a professional high school based in the Rho Municipality (Milan Province, Italy). The scope of the installation is that of providing:

- safety, by dilution of indoor contaminants;
- indoor air quality;
- thermal comfort;
- improved energy efficiency;
- reduced operational and maintenance costs.
The room identified for the training rig is the technical laboratory number 2 (Room TERM-2 in the following sections) located on the ground floor of the north-eastern area of the building, assigned to laboratories (Fig. 1).

(a)  
(b)  

**Fig. 1.** A google map photo of the school from above (a) and from the front (b), with the identified Room TERM-2 located on the ground floor of the north-east area of the building, assigned to laboratories.

The main features of the room are listed below (Fig. 2):

- net floor area 70 m²;
- height 4.56 m;
- net volume 319 m³;
- rated occupation 30 people;
- the only boundary surface to the outdoor environment faces the north-east.

**Fig. 2.** Floor plan and section of Room TERM-1 and Room TERM-2.
The two rooms are nearly of the same size and both connected to the main heating system of the school building with radiators. The main difference is that Room TERM-2 is provided also with the mechanical ventilation system that supplies air for ventilation during the heating and cooling seasons, whereas Room TERM-1 does not.

A relevant feature of the installation is the monitoring system, recording data of:

- outdoor temperature, relative humidity, and CO₂ concentration;
- indoor temperature, relative humidity, and CO₂ concentration for both Room TERM-1 and Room TERM-2;
- electric consumption of the unit.

The all-air ducted air conditioning and ventilation system was provided by AiCARR’s manufacturer members. A simplified scheme is shown in Fig. 3. It has a single circuit (R410A) with a rotative compressor; the rated performance is reported in Table 1. The evaporator is fed by extract air from the treated room to be exhausted (coil 2) and by the outdoor air to be let in (coil 1) during HP and AC operation, respectively. As is well known, this allows for very high COP and EER as the temperatures are much more favourable than traditional HP/AC.

The system has a minimum air flow rate of 1000 m³/h, and a maximum of 1900 m³/h. In this application, the system was set to operate at a fix air flow rate of 1500 m³/h both in the heating and cooling season (determined according to Section 5.3.12 “Air purity” of the Italian Ministerial Decree of 18 December 1975 [24], with a fix air temperature set point (T_{ETA,set} in Table 2) of 22 °C and 26 °C respectively. As a matter of fact, the ventilation system faces only ventilation loads, while heating loads are faced by the radiators. No cooling load (or very low) is provided by the system (Fig. 4).

Fig. 3. Simplified functional diagram of the air ducted air conditioning and ventilation system (the four-way valve and the fans are not drawn).
Fig. 4. Pictures and layout of the all-air ducted air conditioning and ventilation system of Room TERM-2 (courtesy of AiCARR).
Table 1. Nominal data for the air-ducted air conditioning and ventilation system.

<table>
<thead>
<tr>
<th>Air flow rate</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal air flow rate</td>
<td>m³/h</td>
<td>1300</td>
</tr>
<tr>
<td>Maximum air pressure (supply)</td>
<td>Pa</td>
<td>630</td>
</tr>
<tr>
<td>Maximum air pressure (indoor)</td>
<td>Pa</td>
<td>630</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal cooling power</td>
<td>kW</td>
<td>10.6</td>
</tr>
<tr>
<td>Post-heating power</td>
<td>kW</td>
<td>2.70</td>
</tr>
<tr>
<td>Compressor power</td>
<td>kW</td>
<td>2.91</td>
</tr>
<tr>
<td>EER</td>
<td></td>
<td>4.57</td>
</tr>
<tr>
<td><strong>Heating</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal heating power</td>
<td>kW</td>
<td>5.93</td>
</tr>
<tr>
<td>Compressor power</td>
<td>kW</td>
<td>0.71</td>
</tr>
<tr>
<td>COP</td>
<td></td>
<td>8.38</td>
</tr>
</tbody>
</table>


2.3 Description of the calculation

Based on the data monitored and reported in Section 3.1, the main results in terms of energy consumed, plant efficiency, and CO₂ concentration in the rooms were calculated (Section 3.2).

Using the information from the ventilation unit shown in Fig. 3 and the set-point temperatures, the thermal power in the condenser and the evaporator of the HP/AC unit was calculated, as reported in Table 2.

Table 2. Main parameters and control logic of the ventilation unit for Room TERM-2.

<table>
<thead>
<tr>
<th>Air flow rate (V, m³/h - ach)</th>
<th>Heating</th>
<th>Cooling</th>
<th>Off / Heating / Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 - ~5 h⁻¹</td>
<td>IF TETA&lt;TETA,set,heating THEN Heating ELSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500 - ~5 h⁻¹</td>
<td>Pcond=Pevap+Pel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T air inlet (T_SUP, °C)</td>
<td>24</td>
<td>22</td>
<td>IF TETA&lt;TETA,set,cooling THEN Cooling ELSE Off</td>
</tr>
<tr>
<td>T air extract (T ETA,set, °C)</td>
<td>22</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Condenser thermal power (Pcond, kW)</td>
<td>Pcond=(ρE·V/3600)·4.187·(T_SUP-TODA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporator thermal power (Pevap, kW)</td>
<td>Pevap=(ρE·V/3600)·4.187·(TODA-T_SUP)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

In this section, we present the main monitored data (Section 3.1) and the result of energy consumption and indoor air quality (Section 3.2) on an annual basis. Data were monitored with a time step of 5 minutes from March 31st 2022 until February 12th 2023. The following Sections 3.3 and 3.4 provide the same data daily basis for a week during the heating and cooling period (November 26th 2022 - December 2nd 2022 and June 28th 2022 – July 4th 2022, respectively).
3.1 Annual data monitoring

Fig. 5 presents the annual data for the indoor ambient air temperature, relative humidity, and CO₂ concentration for Room TERM-1 (where no Controlled Mechanical Ventilation system is present), and Room TERM-2 (with Controlled Mechanical Ventilation). The temperature and humidity curves exhibit quite similar behaviour, given that both rooms are used for the same purpose, and the ventilation unit caters to ventilation load, not the heating and cooling loads (as depicted in Fig. 6a, based on external air conditions). However, Room TERM-2 demonstrates a consistently lower CO₂ concentration, highlighting a significant advantage of mechanical ventilation.

Fig. 6b illustrates the electrical energy consumption of the ventilation unit, corresponding to the operating periods of the system, as detailed in Table 3.

Table 3. Operation mode in different periods of the ventilation unit for Room TERM-2.

<table>
<thead>
<tr>
<th>Period</th>
<th>Operation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 31st 2022 – April 30th 2022</td>
<td>Heating</td>
</tr>
<tr>
<td>May 1st 2022 – May 30th 2022</td>
<td>Off</td>
</tr>
<tr>
<td>June 1st 2022 – July 12th 2022</td>
<td>Cooling</td>
</tr>
<tr>
<td>July 13th 2022 – September 4th 2022</td>
<td>Off</td>
</tr>
<tr>
<td>September 5th 2022 – December 12th 2022</td>
<td>Heating</td>
</tr>
<tr>
<td>December 13th 2022 – January 8th 2023</td>
<td>Off</td>
</tr>
<tr>
<td>January 9th 2023 – February 12th 2023</td>
<td>Heating</td>
</tr>
</tbody>
</table>

Fig. 5. Annual data of indoor ambient air temperature, relative humidity, and CO₂ concentration for Room TERM-1 (no Controlled Mechanical Ventilation) (a) and Room TERM-2 (with Controlled Mechanical Ventilation) (b).

Fig. 6. Annual data of outdoor external air temperature, relative humidity, and CO₂ concentration (a); electrical energy consumed by ventilation unit (b).
3.2 Annual energy and CO₂ concentration results

Fig. 7a presents annual data on the thermal power in the condenser and the evaporator (presenting useful and rejected heat during the heating and cooling season, respectively) and the electrical power consumed by the ventilation unit. These values were calculated using the equations described in Table 2. Consequently, in some time step they assume a negative value and have not been considered. The energy efficiency indexes (COP and EER for heating and cooling season, respectively) were calculated as the ratio of thermal power and electrical power (in the condenser and the evaporator for the heating and cooling season, respectively, illustrated in Fig. 7b). Notably, this type of unit can achieve very high values as a result of the favourable temperatures of the outdoor air during the cooling season (in the evaporator) and the heating season (in the condenser).

Fig. 7. Annual data of thermal and electrical power (a); Energy efficiency indexes (COP and EER for the heating and cooling season, respectively) and the ventilation unit operation mode (b).

As is well known, the absence of correct ventilation with outdoor air increases the concentration of CO₂ inside classrooms, posing the risk of superpassing the maximum levels allowed for the difference between internal and outdoor concentration. The UNI EN 16798-1 [25] standard sets this limit at 800 ppm for indoor air class II, resulting in a potential increase in inattention and learning loss. Fig. 8 illustrates this difference for the two laboratory rooms. Particularly in the last part of the monitored period, the effectiveness of the ventilation unit in Room TERM-2 in reducing the difference in CO₂ concentration compared to Room TERM-1 can be observed.

Fig. 8. Annual data of the difference in CO₂ concentration between the indoor and outdoor environment for the two laboratories.
3.3 Weekly data monitoring, energy, and CO₂ concentration results during the heating period

Fig. 9 and Fig. 10 present daily data on indoor ambient air temperature, relative humidity, and CO₂ concentration for the two laboratory rooms during one week of the heating period. As mentioned in Section 3.1, the temperature and humidity curves exhibit quite similar behaviour in the two rooms. From these figures and Fig. 11, it is observed that on some days, the CO₂ concentration in Room TERM-2 does not decrease with respect to Room TERM-1: this could be caused by a particular “fireplace effect” due to the contemporaneous opening of the windows and the door of the room that call the air from the hallway to the room.

![Fig. 9](image1.png)

**Fig. 9.** Weekly data (during the heating period) of the indoor ambient air temperature, relative humidity, and CO₂ concentration for Room TERM-1 (no Controlled Mechanical Ventilation) (a) and Room TERM-2 (with Controlled Mechanical Ventilation) (b).

![Fig. 10](image2.png)

**Fig. 10.** Weekly data (during the heating period) of the outdoor external air temperature, relative humidity, and CO₂ concentration (a); electrical energy consumed by the ventilation unit (b).
Fig. 11. Weekly data (during the heating period) of the difference in CO₂ concentration between the indoor and outdoor environment for the two laboratories.

Fig. 12 presents the thermal and electrical power of the ventilation unit and its COP during the three days of operation in that week.

(a) 

(b) 

Fig. 12. Weekly (during the heating period) thermal and electric power (a); energy efficiency indexes (COP) and ventilation unit operation mode (b).

3.4 Weekly data monitoring, energy, and CO₂ concentration results during the cooling period

For completeness, the data of previous Section 3.3 are reiterated here on a daily basis for a week during the cooling period (Fig. 13, Fig. 14, Fig. 15, Fig. 16). Similar considerations apply.
Fig. 13. Weekly data (during the cooling period) of indoor ambient air temperature, relative humidity and CO\textsubscript{2} concentration for Room TERM-1 (no Controlled Mechanical Ventilation) (a) and Room TERM-2 (with Controlled Mechanical Ventilation) (b).

![Fig. 13](image1)

Fig. 14. Weekly data (during the cooling period) of the outdoor external air temperature, relative humidity, and CO\textsubscript{2} concentration (a); electrical energy consumed by the ventilation unit (b).

![Fig. 14](image2)

Fig. 15. Weekly data (during the cooling period) of the difference in CO\textsubscript{2} concentration between the indoor and outdoor environment for the two laboratories.

![Fig. 15](image3)

Fig. 16. Weekly (during the cooling period) thermal and electric power (a); energy efficiency indexes (EER) and ventilation unit operation mode (b).

![Fig. 16](image4)

4 CONCLUSIONS
Investigating a real operating ventilation system poses significant challenges in pandemic awareness time. After several theoretical and experimental (based on infection data) works appeared, a good monitoring system was helpful for a better understanding of mechanical ventilation, its capabilities, and limitations.

As articulated in the paragraph “Results and discussion”, not all of the results can be completely justified using the information available, and some of those results are not in accordance with expectations (see comments for Fig. 9 and Fig. 11). Significant improvements could be made, such as, for example, increasing the number of CO₂ sensors in rooms to monitor CO₂ distribution and calculate the effective “air-renewal rate”, as well as possible stratification or ventilation short-circuit phenomena.

Despite this, the experimental results presented are an encouragement to go through the subject and are also a promising starting point in the investigation of the ventilation efficiency not predicted but monitored over a real working application.

References


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the execution of school building works (in Italian, “Norme tecniche aggiornate relative all’edilizia scolastica, ivi compresi gli indici di funzionalità didattica, edilizia ed urbanistica, da osservarsi nella esecuzione di opere di edilizia scolastica”)