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Monitoring the Indoor Air Quality: A Case Study of Passive Cooling from Historical Hypogeal Rooms

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Abstract: Attaining a good level of internal comfort is possible by controlling various parameters. Among all, the thermo-hygrometric comfort and the indoor air quality are of fundamental importance. This research is developed with the aim of verifying the indoor air quality following the installation of a passive cooling device in a historic building located in the province of L'Aquila in the municipality of Poggio Picenze in climatic zone E. This research aims to verify the functioning of a ventilation duct installed between the hypogeal and the second level of the structure that was installed to obtain air recirculation by exploiting the inertial potential of the hypogeal room. The first phase of the research was aimed at thermo-hygrometric monitoring using sensors installed on-site and controlled remotely in order to verify the operation of the device. The second-phase object of this text was useful in investigating the acquired indoor air quality level.

Keywords: passive cooling; natural ventilation; thermal comfort; sensors; indoor air quality

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1. Introduction

In Europe, in recent years, the theme of energy improvement of historic buildings has had an increasing resonance thanks to scientific research in the sector and to European and national directives on the energy efficiency of buildings [1–5]. As part of the energy improvement of historic buildings, the issues most addressed and partially resolved are those relating to the winter performance of the structures and, therefore, to the management of the energy consumed for heating. However, we must consider that a third of the world's population lives in areas with hot–dry or hot humid weather whilst internal continental areas, even in high latitudes (50°), are characterized by summer temperatures over comfort levels [6]. In Europe especially, the energy employed in the air conditioning systems during the summer period is constantly increasing. A new challenge for research therefore consists in identifying solutions to improve summer comfort in these buildings, thus limiting energy consumption and reducing CO_2 emissions [7].

A more complete way to look at internal comfort is to deal with both the thermo-hygrometric conditions and the internal environmental quality; this implies also having to check the quality of the air in terms of the pollutants present in it, as well as the temperature and humidity. Natural ventilation, as well as being an excellent tool for passive cooling, is one of the most interesting aspects related to opening systems in buildings (trickle vents in windows, occupant behavior related to window opening, the window's open area, openable area vs. window/glazing area) and is essential for controlling the quality of the indoor air and therefore for well-being. Air exchange obtained by natural ventilation helps in the dispersion of polluting elements from various internal sources (appliances, fireplaces, furnishings, smoke, gassing rates from materials etc.) that accumulate within the spaces used in both residential and public/work environments [8,9].

Good indoor air quality, that the Air Infiltration and Ventilation Centre defines as air that is free of pollutants that cause irritation, discomfort or ill health to occupants, is achieved when the mixing of fresh air from outdoor and internal air is complete, or when the number of air changes is adequate for the intended use of the room and the number of its occupants [10,11]. ASHRAE 62/99 "Ventilation for acceptable indoor air quality" defines good quality air, "the air towards which the majority of occupants (>80%) do not express dissatisfaction and in which there are no contaminants to an extent dangerous". The Italian Ministry of the Environment, on the other hand, defines internal pollution as "any alteration in the chemical, physical and biological characteristics of the air, determined both by variations in the concentration of its normal constituents and, above all, by the presence of substances foreign to its normal composition capable of determining of harm and/or harassment to humans". Ultimately, good air quality is achieved by maintaining healthy, clean and not smelly air indoors. However, the literature on humidity suggests that inadequate ventilation in residential buildings constitutes a major risk factor for health effects (cough, wheezing, asthma and respiratory tract infections), but since the air taken in the case study comes from hypogeal rooms, it was investigated what the influence of this ventilation could have on air quality.

During natural ventilation phenomena, the movement of air and its renewal are higher the greater the differences in temperature and air pressure between two different environmental portions are. The principle explained is easily applicable to new buildings, but not easily to historical buildings that, on the contrary, have important values to preserve that do not allow intrusive intervention. In this study, the natural ventilation of a XV cent. historic building located in Poggio Picenze (AQ) was improved by installing a ventilation duct during the restoration works of the structure, which was needed because of the big 2009 earthquake [12–15]. This application allowed us to confirm that, through the installation of the duct, adequate levels of internal thermo-hygrometric comfort were achieved, but the air introduced by the duct and taken from the hypogeal rooms of the same building worsened the indoor air quality (IAQ) in the rooms that were ventilated [12–15].

2. Indoor Air Quality in Historical Buildings

It has been proven that exposure to toxic and radioactive airborne pollutants in confined environments, industrial or otherwise, is generally higher than that relating to pollutants in the atmosphere [16–18]. Nevertheless, the regulations require, in the context of this type of environment, strict controls only for those of an industrial nature (which involve the so-called "professional" risks, which affect well-defined categories of workers involved in particular activities), paying less attention to those used for life and work activities (commonly defined indoor) such as homes, schools, hospitals, offices, public buildings, means of transport etc. However, it was found that the pollution present in such environments, due to substances emitted by sources both internal (structural or relating to the occupants) and external to the environment itself, is anything but negligible, and the risks present for the occupants are of the same order of magnitude as those encountered in industrial plants [19]. Generally, the term indoor pollution refers to this particular form of pollution that affects the air and, more generally, the internal environment of confined places in which human activities take place, including those of a leisure or rest nature, i.e., places intended for the regular occupancy of people. With the increase in oil costs, the strategies for approaching the problem are directed towards two prevailing directions: the increase in the insulating power of the perimeter walls, roofs and windows in order to reduce losses due to conduction, and the increase in air tightness of doors and windows to minimize losses due to convection and dispersions. In general, such an economic need, increased by the belief that the main polluting sources reside outside, has directed most of the interventions prepared mainly towards the fight against drafts, with a consequent reduction in air exchange rates [20,21]. The buildings have been built or equipped increasingly airtight, also reducing infiltrations and, consequently, the ventilation rates have been reduced. The "sealing" of homes, but especially that of offices, had immediate consequences: there was a rapid increase in allergic and lung diseases and in the speed of spread of infectious diseases among users of the same building. It was also found that the situation was worse in buildings equipped with air conditioning. In the current period of the COVID-19 pandemic, these problems are even more evident. Natural ventilation therefore represents one of the most interesting aspects related to window and door frames and is essential for controlling the quality of the indoor air and therefore for well-being [11–38].

The case of historic buildings requires further specifications and investigations due to the particular constructive characteristics of the structures. In fact, both the masonry type, its thermal mass and the openings system greatly influence, for better or for worse, the air tightness of the envelope and the air recirculation. Even in the case of historic buildings, the thermal benefits found in a highly insulated envelope must be weighed by the impact that the retrofit can generate on the internal original microclimate, the maintenance of which is essential for the preservation of the value. In fact, while the internal insulation is often applied during the refurbishment for compatibility reasons, this represents one of the causes of the condensation risk and mold on the internal surface of the structure, modifying the original thermal characteristics of the masonry and consequently compromising the preservation and protection of the building fabric and its artistic values [22–27].

It can be said that in historic buildings, over the centuries, a spontaneous balance has always been created between natural ventilation through windows and air infiltrations and the metabolic activity of the occupants, capable of guaranteeing an internal microclimate suitable for the conservation of the structures in good condition to present day [28–31]. Today, the needs for energy improvement, intervening on the envelope and on the thermal and electrical systems, even if in a minimal way, have compromised this balance [32–36]. This balance should be wisely reconstructed through appropriate strategies for controlling the thermo-hygrometric conditions of the structure when it is in use, depending on the outdoor conditions (climate and location of the structure) and the indoor ones (metabolic activity, number of occupants/users) [37–41].

In addition to the refurbishment issue, it is necessary to take into consideration the relationship between users and the building; it has been demonstrated by several studies that delegating to the user the responsibility for controlling the humidity of the environment through air changes via windows, does not guarantee a good result in terms of indoor environmental quality (IEQ). Precisely in relation to the use of these buildings, it is worth remembering that the change in use that often characterizes them (structures once used as private homes today host museums or public offices) deserves adequate attention in relation to the alteration of the original internal microclimate [42,43]. Therefore, although natural ventilation systems would be the best to apply having a low impact in terms of compatibility, to achieve adequate levels of comfort and ensure adequate conservation of the structure (avoiding the formation of mold and pollutants), natural ventilation has been proven to be insufficient. For this reason, the research on innovative systems and devices capable of improving air changes (by activating passive and/or mechanical ventilation in the structures) is necessary to improve the performance of the architectural heritage and the comfort of its occupants [2].

The application of traditional mechanical ventilation systems cannot be easily applied to the architectural heritage due to the conspicuousness and invasiveness of the system, which prevents it from being correctly integrated into the original structure for reasons of formal and often structural compatibility. For this reason, Task 59 of the International Energy Agency (IEA SHC) [44] and the ATLAS Interreg Alpine Space project [45] were born, with the aim of adapting traditional approaches on mechanical ventilation to the renovation of historic buildings. The challenge in designing suitable ventilation systems lies in balancing compatibility requirements with efficiency requirements. Therefore, research has preferred to opt for the enhancement of passive systems, often already present in the building, such as original ventilation chimneys or wind towers. In this study, the theme of the ventilation duct refers to the specific case of exploiting the differences in temperatures between the hypogeal rooms and the rooms to be ventilated on the first level of the building. Previous studies of this research have shown that this application has brought advantages in terms of ventilation rate. On the other hand, since the ultimate goal of these applications lies not so much in the quantity of air flow set in motion but rather in the quality—essential for the well-being of the building and occupants—a specific investigation was necessary.

3. Materials and Methods

The complete research methodology is illustrated in Figure 1 and concerns 6 research phases as follows:

1. Analysis of the theoretical models of ventilation chimneys;
2. Choice of models and system design;
3. Modeling and simulations of the system;
4. Installation of the conduit with sensors for monitoring;
5. Validation of the model and the results;
6. Analysis of air quality.

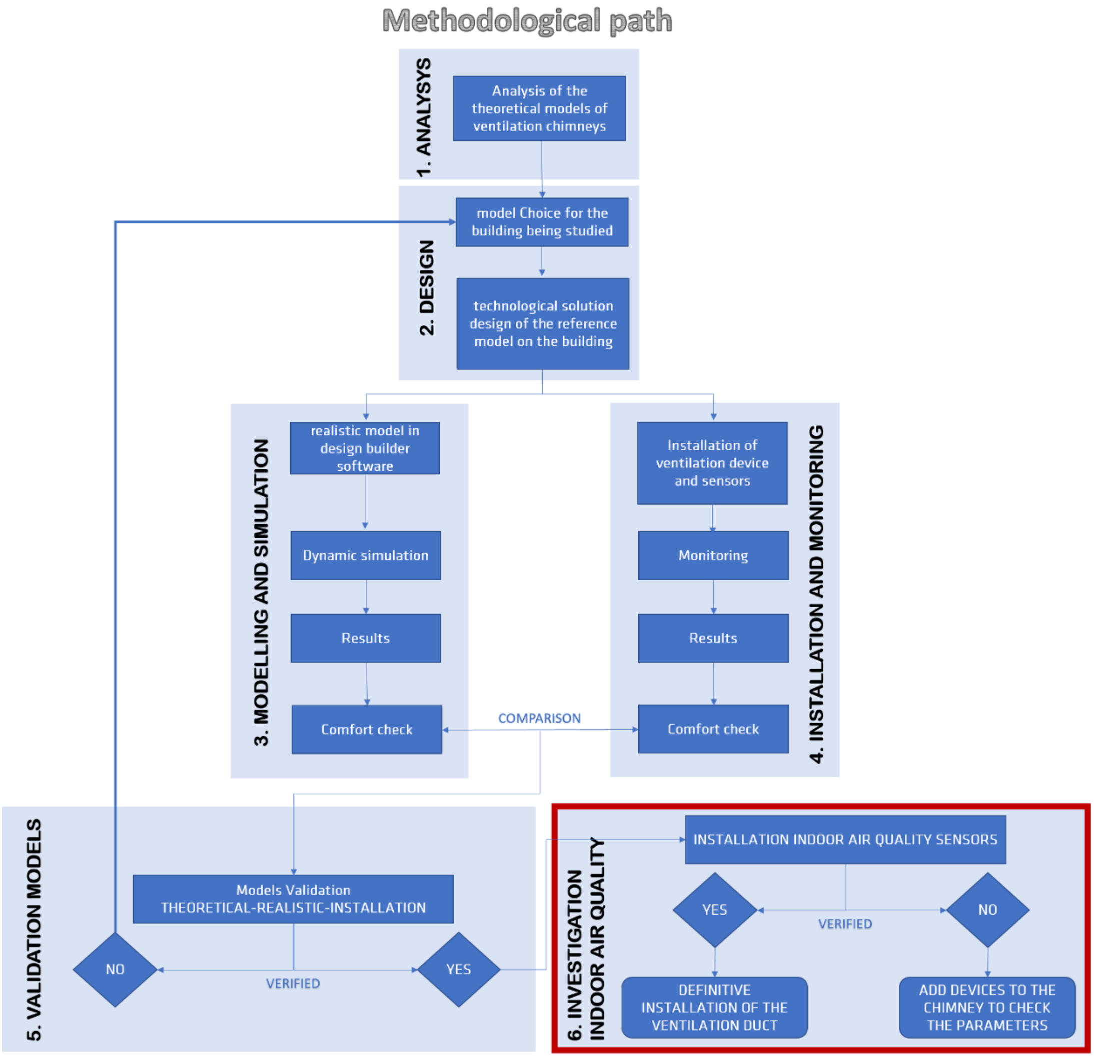


Figure 1. Flow chart of the research methodology. The part of the research covered by this text is in red.

Since the research concerns drawing fresh air from the cellars of the case study, located at the hypogeal level, in this paper the analyses of the air quality transported by the ventilation duct was described. The analyses were carried out through the installations of further sensors pursued to the scope [12–15]. In this way, it was possible to evaluate the overall effectiveness of the performance improvement intervention of the structure, including in the evaluations of both the issue of thermo-hygrometric comfort and that related to IAQ.

In particular, this paper dealt with point 6, related to the investigation on the indoor air quality. This therefore represents the final step of our research on the performance improvement of the historic building in the summer regime reached due to the implementation of the sensors applied in the previous phases.

Point 6 is related to the following steps:

Step 1: Installation of the air quality sensors on the building;

Step 2: Monitoring of the indoor and outdoor conditions during the maximum operating period of the duct detected in phase 5;

Step 3: Collecting and analyzing data from the IAQ monitoring system.

3.1. The Historical Building Analysed

The IAQ analyses were carried out on "Palazzo Galeota" (Figure 2), a 15th century building of elevated historical and architectural value situated in Poggio Picenze, L'Aquila (Italy). The structure, built on ancient hypogeal built environments, was damaged by the 2009 earthquake that in 2009 hit the Abruzzo region [14]. The building suffered serious damage, such as the partial collapse of floors and cracks along the bearing walls. The structure has not yet been repaired but has been secured by a still standing external metal pipes grid. Palazzo Galeota, constructed in mixed masonry brickwork stones, had a wood covering. In particular, the palace showed many other historical features (e.g., original windows with wooden frames and single pane glass), no thermal insulation for the historical envelope and no heating, ventilation and air conditioning (HVAC) systems.

Figure 2. Galeota Palace in Poggio Picenze (AQ) (Google Earth).

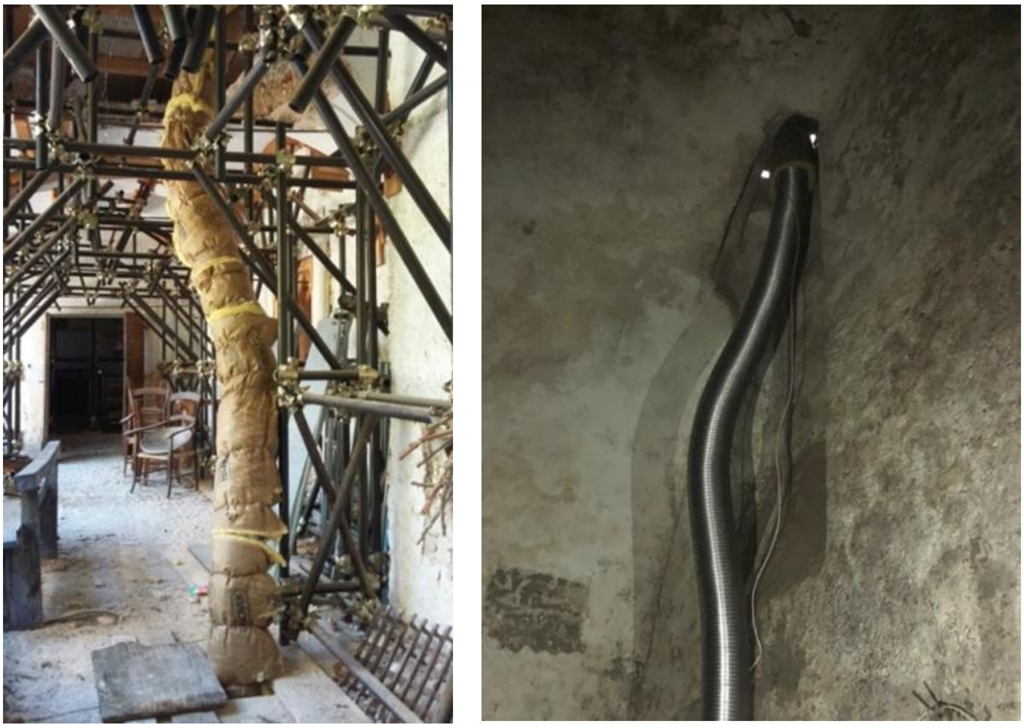
During the restoration process (currently in progress), we imagined an energy performance improvement for the historical building. By analyzing the climatic condition of the location and the environmental behavior of the envelope (results from models and dynamic simulations are available in previous publication [12]), we focalized the enhancement on summer performance through the installation of a ventilation chimney prototype. The chimney from the warmer areas of the second level rooms descended to the hypogeal spaces that have a lower temperature and came into contact with water pools, since both the air intake and the humidification favor the movement of induced air currents useful to air renewal and cooling. The duct as installed today is still the prototype version.

3.2. Installation of the Ventilation Duct and Monitoring with Sensors Network

In the palace, a duct that connected the basement to a room at the first floor was installed, transporting cold air from the hypogeal level (Figures 3 and 4). The duct, realized in steel material, had a circular section of 25 cm diameter and was 10 m high. For the duct, a flexible stainless steel pipe was used, which is commonly inserted into existing flues, and soft rock wool for insulation. None of the already insulated pipes were used because in the initial experimentation phase of the ventilation, the insulation was gradually removed. After the 2009 earthquake, the historical windows were removed and the openings were sealed with a transparent PVC sheet in order to favor the solar gains and an increase of indoor temperature, producing a hothouse effect similar to the previous glazing system.

Monitoring through temperature, humidity, rainfall and wind direction sensors enabled us to obtain information about the effectiveness of the duct and showed that the maximum operating period was from July to September [12]. This means that the greatest amount of air transferred from the hypogeal rooms to the rooms to be cooled corresponds to the same period of maximum functionality of the duct; for this reason, the monitoring of air quality through special sensors was carried out exclusively between the months of July and September.

A sensor network usually provides several nodes, wireless or wired and distributed in the monitoring area, which periodically send data detected by the sensors to a collection point, known as a sink, base station or gateway (Figure 4). Here, the data is collected and sent to a remote recording system for further processing. The monitoring presented in this study was composed of elements capable of measuring, processing and sending data collected by sensors to a central station through a network protocol: an application necessary for data processing and storage, an external interface for data consultation and analysis, a database and a web server with a specific web application. Specifically, in phase 6 of the research, the sensors had the task of monitoring the cooled environment at level 2 and the external climatic conditions through a weather station installed on the roof (Figures 5–7).



(**a**) (**b**)

Figure 3. The duct once installed (**a**) in the cellar; (**b**) on the ground floor under the arcade.

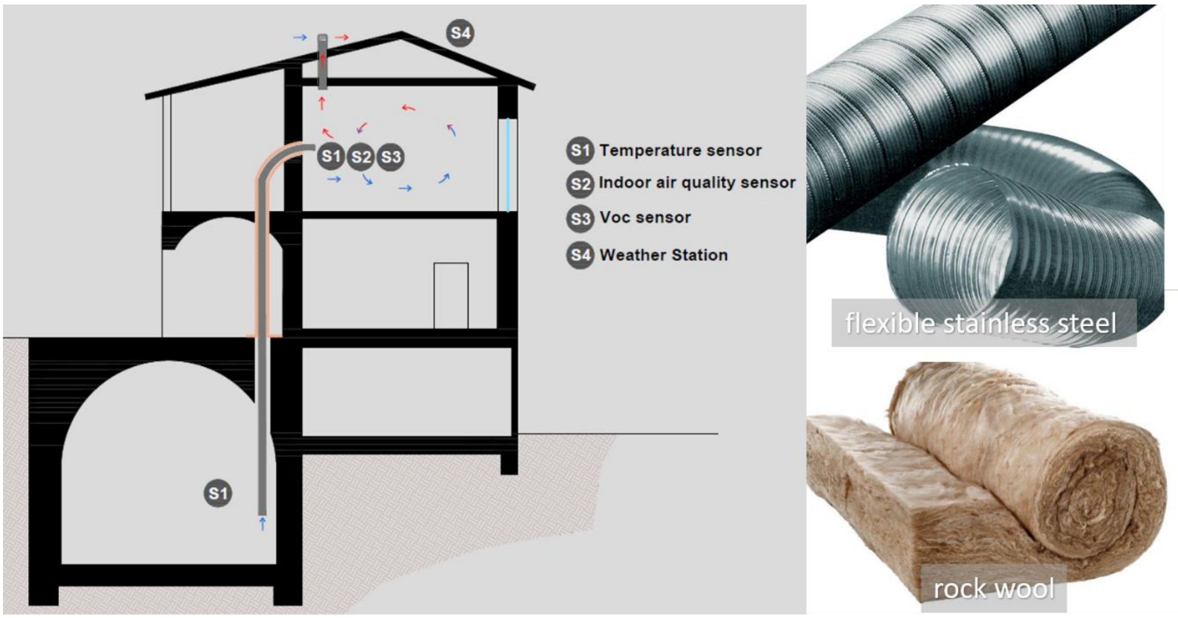


Figure 4. Scheme of the duct route through the floors (basement–ground–first floors). The materials used are steel and rock wool.

(**a**) (**b**)

Figure 5. Base station (Arduino system). (**a**) Arduino System assembled (**b**) Arduino System with the cover.

(**a**) (**b**) (**c**)

Figure 6. Sensors for indoor air quality: (**a**) air quality, (**b**) gas sensor and (**c**) VOC.

(**a**) (**b**)

Figure 7. In the red circle the weather station installed on the roof: (**a**) weather station (**b**) weather station on the roof of the Palace.

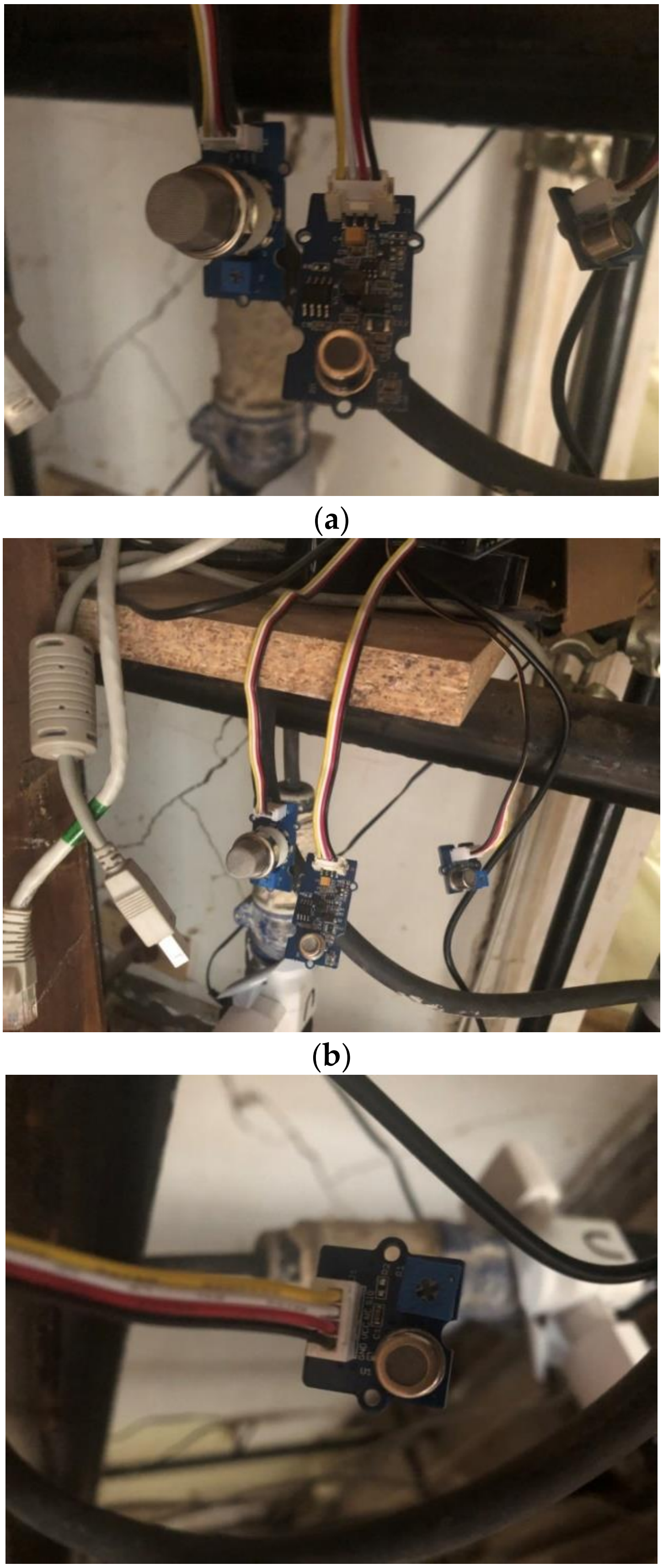
4. Results

VOC and air quality sensors (CO_2, MQ2, HCHO, IAQ) were installed in the room reached by the ventilation duct prototype (Figure 8). The Grove Air Quality Sensor V1.3 is an indoor air quality sensor, which can detect a wide variety of gases such as carbon monoxide, alcohol, acetone, solvents and formaldehyde in a range between 10–1000 ppm. The sensors were calibrated in the laboratory and tested before installation. These sensors had the task of checking the indoor air quality in the months of July and August, when the system is at maximum operating speed, and, consequently, the air flow is higher [13]. The data were collected using the Arturo software developed by the Department of Engineering, Computer Science and Mathematics (DISIM), University of L'Aquila, Figure 9 shows the software interface.

The concentration of pollutants from internal sources present in the air, which are generally of origin of the following:

- Chemistry: carbon monoxide and dioxide, nitrogen dioxide, benzene, styrene etc.;
- Biological: molds, bacteria, mites, pollen, fungi etc.;
- Physics: radon gas and electromagnetic fields;
- From human activities, such as cooking or smoking;
- Linked to the presence of people, animals or plants;
- Construction materials or finishes, furnishings and accessories (curtains, carpets and fabrics).

In the case of hypogeal rooms, the concentrations of pollutants is mainly due to sources of biological and chemical origin; therefore, the investigation focused on these types of pollutants.



(a)

(b)

(c)

Figure 8. Installed sensors: (**a**) indoor air quality sensors, (**b**) gas sensors and (**c**) VOC sensors.

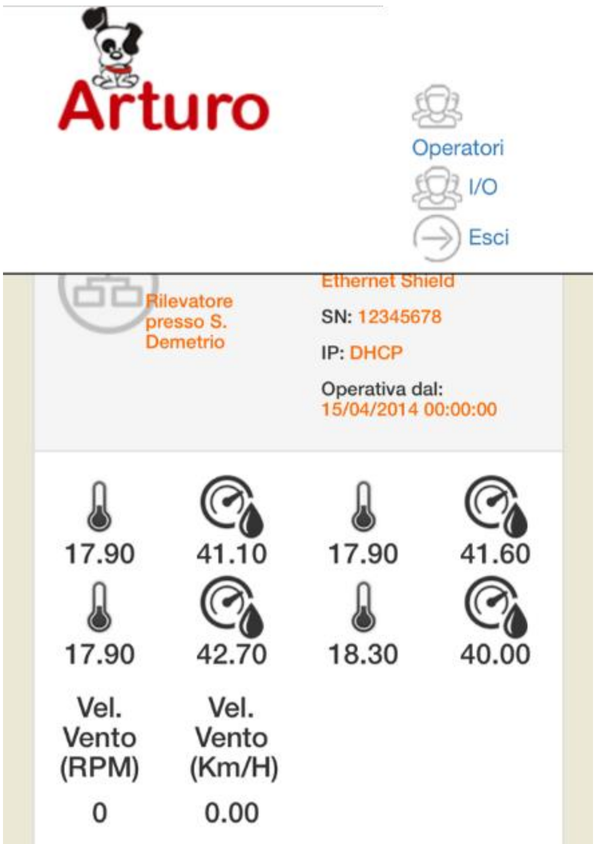


Figure 9. The software Arturo developed by DISIM, to collect the data monitored.

The data were analyzed starting from the results of the previous research phase in which it was proved that the operation of the ventilation device increases its performance when there is a large difference in temperature between the external and internal air. This was positive in the months of July, August and September, the months also monitored for air quality. In fact, natural internal ventilation brings benefits to air quality if the air introduced is not polluted. The purpose of the following analyses was to correlate the internal temperature with the air quality in order to also verify the correct operation of the device in this aspect. It was verified through monitoring that the daily temperatures follow the trend of the temperate climate with strong nocturnal variations compared to the daytime (Table 1). Therefore, in the graphs, the averages of the daytime hours were considered.

Table 1. Air quality monitoring data.

Date	MQ2 (ppm)	HCHO (ppm)	Air Quality	Medium Temp. (°C)
19 July 2018	0.19	0.12	10.89	22.00
27 July 2018	0.19	0.11	7.50	20.50
10 August 2018	0.19	0.11	9.62	23.00
16 August 2018	0.19	0.11	9.72	19.00
17 August 2018	0.19	0.10	10.24	19.50
18 August 2018	0.19	0.10	7.10	18.50
19 August 2018	0.19	0.10	6.90	19.00
24 August 2018	0.19	0.09	7.52	19.00
18 September 2018	0.19	0.09	7.45	19.00
21 September 2018	0.19	0.09	6.75	19.50

The results were entered into the linear diagrams below to evaluate the trend of the data.

From the graph in Figure 10, one can see a linear trend without particular increase for the data monitored by the MQ2 sensor (gas sensor), as we are, among other things, in an isolated and not particularly busy area. For the green curve relating to formaldehyde data, we see an improvement, as the operation of the ventilation duct improves this parameter.

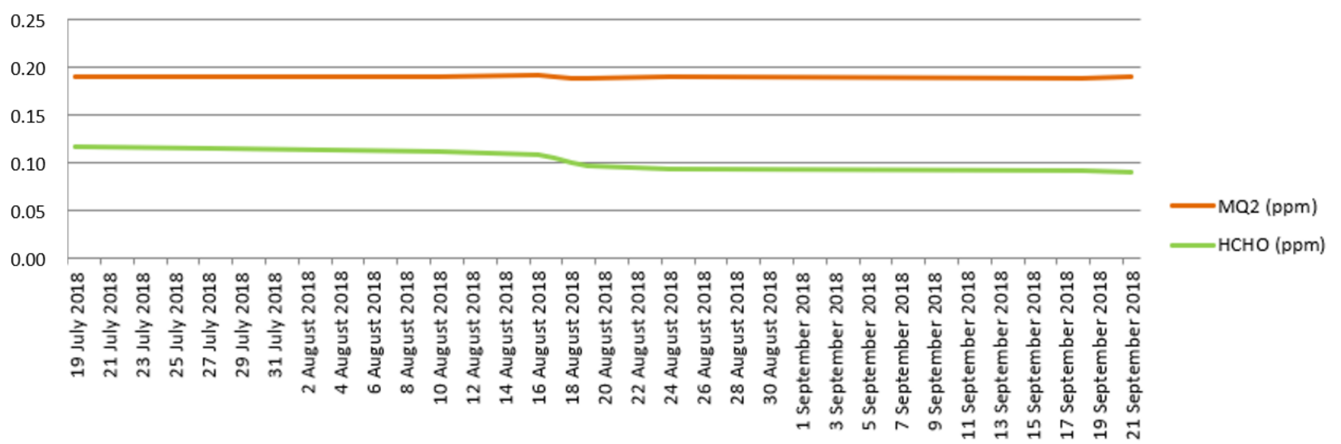


Figure 10. Linear graph of the monitoring of data from the VOC sensor (volatile organic compounds). Curve in green is relative to the MQ2 data and in red relative to the HCHO data.

Overall, the graph in Figure 11 shows, however, that with the decrease in temperature, the quality of the indoor air also decreases as a whole, as the curves are almost parallel. This aspect will have to be studied in depth to understand which parameter has the greatest influence and apply the necessary devices in order to reduce indoor pollution caused by the operation of the ventilation device.

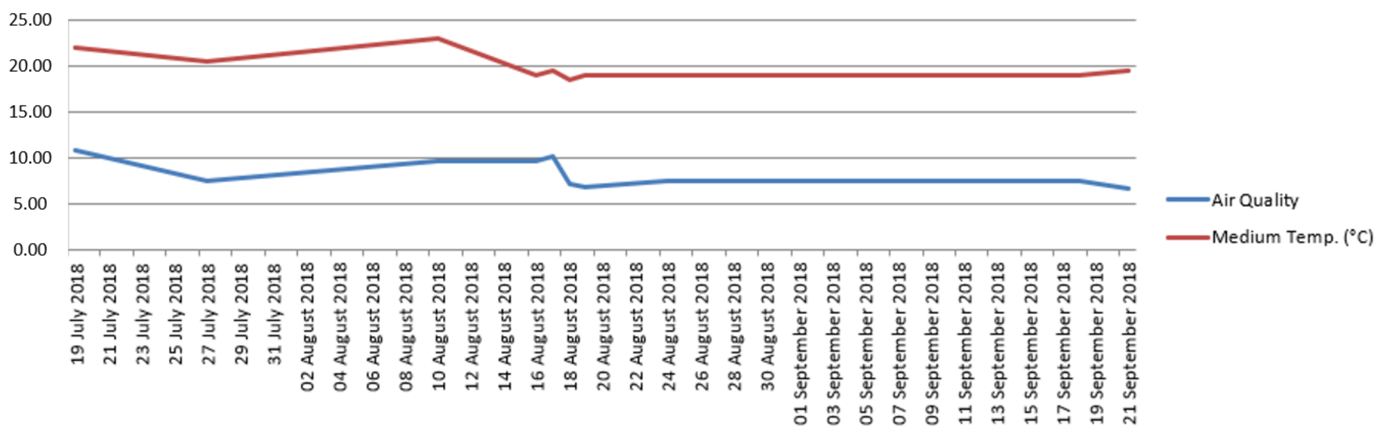


Figure 11. Line graph of air quality and temperature data monitoring.

5. Discussion

This research is part of a broader study of energy requalification techniques for historic buildings, on which it is possible to intervene through interventions with little impact and studied ad hoc for each individual building. In particular, a passive ventilation system was studied that can be inserted into existing flues, using the recurrent underground rooms existing in the building types of our areas.

In the first phase, the research was developed on the monitoring of thermo-hygrometric parameters, in order to evaluate the functioning of the device for passive cooling of the rooms, exploiting the temperature difference between the underground rooms and the rooms on the upper floors. The first thermo-hygrometric monitoring gave positive results, obtaining a good level of internal comfort in the rooms where the device was located, especially in the hottest months of the Mediterranean climate from June to September.

In the second phase, the evaluation of the quality of the air exchanged with these rooms was carried out which, in most cases, are very humid rooms and therefore places of development of different types of microorganisms that can affect the air quality of habitable environments.

The part of the research to which this paper refers has shown how tapping into natural resources to improve the performance of architectural heritage is a viable possibility. Historic buildings are in fact often equipped with construction characteristics suitable for use for energy improvement purposes.

In this case, the pre-existing hypogeal space—integral part of the current building, a condition common to most of the historical structures—was exploited. It was shown how it is possible to use the fresh air coming from a hypogeal room which has the characteristic of having almost constant temperatures throughout the year, being hypogeal. Fortunately, hypogeal environments, caves and cavities are widespread in the Mediterranean regions as well as hypogeal environments characterized by the lower temperatures on the upper floors. Therefore, a greater awareness of systems capable of exploiting the natural flow of ventilation could lead to a more "widespread" application in the most varied contexts with consequent savings in terms of energy and fossil resources [7,46,47].

However, in this paper it was shown, through appropriate monitoring with sensors, that the air present in these hypogeal rooms can contain pollutants that are harmful to human health. These pollutants often derive from the intended use of hypogeal rooms as cellars or warehouses, and above all, from the poor air exchange to which they are subject due to the lack of adequate openings or from their complete absence. This condition favors the growth of microorganisms and molds that release pollutants into the air.

The main strength of this research are the results deriving from experimental data and from in situ monitoring. These data provide important information on the actual functioning of the cooling device installed in the historic building under study. At the same time, a limitation of the work consists of the impossibility of a comparison with the use of the device in different conditions, especially climatic ones. In fact, the survey on air quality was carried out only in the period of maximum operation of the ventilation duct: in summer.

Finally, to improve the operation of the duct and to take full advantage of the passive cooling intervention, it would be desirable to adopt filters for the intake air so that air exchange can be guaranteed in the best conditions for the health of the occupants.

In addition to the possibility of improving solutions to the device applied in this research, the possibility of designing a device that exploits a ventilation chimney inserted inside the existing shafts, whose ventilation operation exploits only the extraction of air, was evaluated. This device proved to be effective in activating an air exchange but is not safe with respect to the pollutants it carries into inhabited environments. For this reason, the authors of the paper, supported by the Industrial and Information Engineering and Economics Department (DIIIE) of the Engineering University of L'Aquila, have designed a passive ventilation device which, instead of introducing new air into the room to be ventilated, operates by extraction, thus facilitating the recirculation. This device has been filed as a patent and will be the subject of future research developments.

6. Conclusions

The present contribution aimed at identifying ventilation ducts as passive cooling systems that can be installed on historic buildings and to verify their functioning both from a thermo-hygrometric point of view and of indoor air quality comfort. Passive ventilation devices ensure air exchange, but the air introduced must be clean and free from pollutants, so it is essential to check the related parameters. In this case study, the extracted air came from a cellar, which raises the question of air quality and the need to install additional sensors to monitor air quality in the room to be ventilated.

In this research, the objective of optimizing natural ventilation was pursued by installing a duct that exploited the principle of the chimney effect inside a historic building located in Poggio Picenze (AQ). The functioning of the installed prototype was evaluated first of all from the thermo-hygrometric point of view [12–15] through dynamic simulations with software and, subsequently, through the monitoring and collation of the real data of the site. It later emerged that the removal of air from hypogeal rooms, intended for use in the basement, may have a negative influence on the internal microclimate of the room in which the air is fed. From what has been said, the need has emerged to investigate the microclimate present in confined environments to understand if it is suitable for an optimal life and no anomalies that could negatively affect health, emotional sphere or well-being. In particular, the present study focused on the understanding of the change in the indoor microclimate of the cooled room by the duct through the implementation of the monitoring sensor system installed for the thermo-hygrometric comfort with a system aimed at acquisition of air quality parameters, especially in the months when the performance of the cooling duct was higher. Research has shown that, although general IEQ increases due to natural ventilation, by investigating specific sources of pollution, it is considered necessary to install filtering systems in the duct to improve the air quality parameters in the environments to be cooled.

The studies and analyses carried out revealed the difficulty in obtaining hygrometric conditions in historic buildings such as to guarantee comfort and at the same time protection for the building with only natural ventilation. Along the way of strengthening the construction features of the historic building, a passive cooling system was investigated that would exploit the temperature delta between hypogeal rooms and floors above ground to activate a ventilation chimney.

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