Application of the hybrid ventilation concepts to a real building: a hospice sited in the North East region of Italy

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SUMMARY
Natural ventilation most attractive feature is the ability to combine a reduction in required costs to the capability, when climate and operating conditions are favorable, of ensuring ventilation rates consistent with acceptable indoor air quality and temperature control. Uncertainty about practicing a control on airflows and the unreliability related to the stochastic nature of its driving forces are recognized as being serious challenges to the development of natural ventilation technique. Hybrid technology represents the attempt of combining the benefits of both ventilation strategies in a unique system. This paper presents an application of the hybrid concepts to a real building. Mechanical ventilation is exploited for heat recovery in winter and for meeting ventilation objectives when natural forces are poor. Natural ventilation is applied for indoor air quality and temperature control. In particular, a system of self regulating vents adjusting ventilation rates on the level of indoor relative humidity is analyzed.

KEYWORDS
Energy simulations, Indoor air quality, Hybrid ventilation

INTRODUCTION
This paper addresses the dual challenge of designing a sustainable low-energy building while still ensuring a comfortable and healthy indoor environment. The renovation plan of a heritage building provides the chance for testing the application of the "energy conscious building" concepts to the development of the design phases. The project is characterized by the deep interaction between aesthetical and technological options. Its points of strength are: low environmental impacting materials, insulation of building envelope, control of solar radiation gains, heat recovery and automatic indoor climate control combining benefits of mechanical and natural ventilation.

In particular, the role of ventilation is revised. Ventilation is of major importance for the well-being of people within enclosed spaces and building design has to face the dual challenge of providing good ventilation performance and energy conservation. Actually, energy required for ventilation represents great part of the total energy consumption especially for buildings characterized by high levels of insulation. Combining natural and mechanical systems is a very promising technique. Dealing with the optimization process for ventilation gives the opportunity to span various issues: the definition of the ventilation needs, the adjustment on the airflow rates based on the variation in time of the needs for supply air, the reduction of the energy required by air conditioning and distribution (Santamouris, 2006). The project consists of a pre-existing structure which is to be linked to a new wing. The complex as a whole is intended to become a hospice, a medical structure conceived for terminally ill patients. Spaces and related activities are distributed on two floors which are connected vertically by a large central atrium. Ground level is intended for medical treatment and leisure activities. First floor is meant to hold patients and their relatives. Seven rooms for up to 14 patients are foreseen. Its high occupancy density, causing very large values of internal heat sources as well as internal emissions of body odors, water vapor and CO_2, results in a concern regarding the indoor air quality patients are exposed to along the major period. The integration between building envelope design and the air conditioning system represents the most dominant feature of the project. To achieve the goal of minimizing energy consumption, great attention is paid to integrate the building with its surroundings. The following aspects are exploited: thermal insulation of walls and roof and ensuring the right envelope permeability for enhancing natural ventilation potential; heat recovery to transfer heat from the exhaust to the supply air stream, thus reducing the heat loss due to ventilation (Fehrm, 2002); control of solar gains in order to reduce space heating demand during winter and to minimize cooling requirements in summer; automatic indoor control system which is responsible for the integration between mechanical ventilation and natural controlled airflow. For energy calculations standard hourly data for solar radiation, air humidity and air temperature as they are available for Venice are used (Mazzarella, 1997).

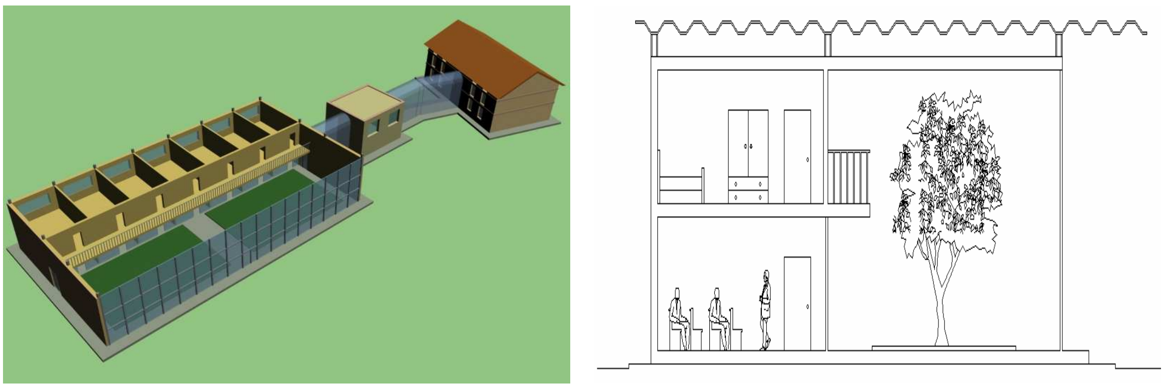

Figure 1. Characterization of the structure and atrium details.

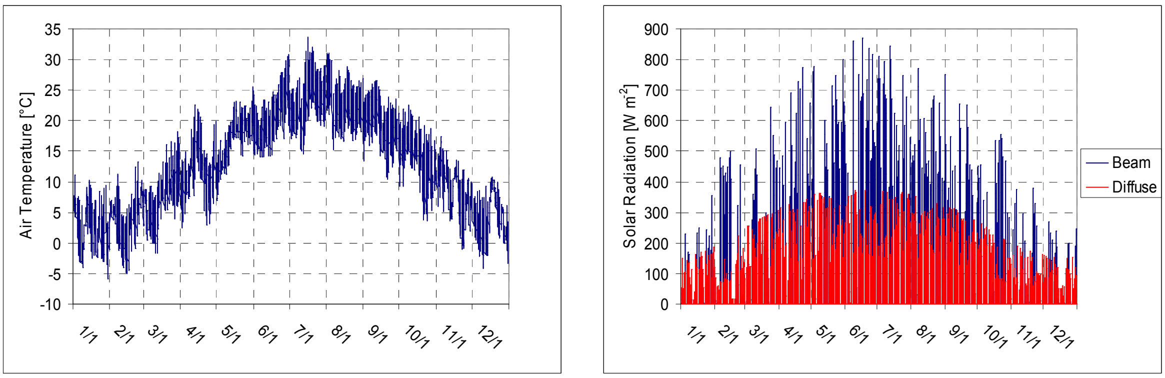

Figure 2. Air temperature and solar radiation on horizontal as they are available for Venice.

METHODS

The evaluation of the energy demand and of the parameters related to indoor air quality is possible through building energy and airflow simulation tools. The calculation of airflows is of great importance for building energy simulation codes, as ventilation represents great part of the thermal coupling between indoor environment and the outside. There are several approaches to simulating airflow phenomena. They can be categorized into macroscopic and microscopic models. The former are known as network or multizone models. These models rely on the idealization of the building system as a collection of control volumes, namely portions of space that are assumed to be characterized by a single value for air temperature and contaminant concentration at any given time. Microscopic models require the domain of interest to be divided into smaller control volumes, each one is then characterized by its own value for temperature, velocity and contaminant concentration. Although network models are not capable of spatial detailed information as they are missing local phenomena such as air velocity profile in a space, they can be easily applied to the whole building system in an affordable way in terms of computational demand.

CONTAM is a multi-zone indoor air quality and ventilation analysis program that enables room-to-room airflow and contaminant dispersal modeling (Walton, 2006). The multizone approach is implemented by drawing a network of elements describing the flow paths, such as windows, doors or HVAC ducts, through which air can move between adjacent zones. Each zone stands for a volume of air that is separated from other volumes by walls, floor and ceiling. As flow paths are brought into the model, i.e. it is specified the mathematical relationship between the flow through each element and the pressure drop across it, the mass conservation condition is imposed on each network node meaning that air can neither be created nor destroyed within every single zone. Conservation of mass at each zone leads to a set of non linear simultaneous equations that is solved at each time step of the simulation, resulting in the determination of node pressures and mass flows between adjacent spaces (Lorenzetti, 2002). As they are available, contaminant concentration within each single zone is calculated as a balance between inward and outward airflows, contaminant generation and removal rates. This paper refers to carbon dioxide as an indicator of indoor air quality because of the correspondence that can be drawn between this gas, which can be related to human occupancy as it is a result of human metabolism and respiration, and other odor causing occupant generated bioeffluents (Persily, 1996).

The building model is set up in TRNSYS environment (Klein, 2000; McDowell, 2003). TRNSYS is a simulation package that enables transient systems analysis. Given a particular problem, the software enables to split it into a series of smaller components (or Types as they are called) that interact with each other. Each component is identified by a unique Type number that relates the component itself to the specific problem which has to be solved. The modular nature of the software makes that components are interconnected in such a way that produced outputs of a Type can serve as inputs to other components. Running a TRNSYS simulation means drawing a flowchart of information from one Type to the other by defining and connecting each individual component.

The building as a whole is schematized as a 3 zone system. Zone 1 stands for the area where rooms for patients are placed. Zone 2 groups all common spaces sited on ground floor. Zone 3 represents the large central atrium which connects the two floors. Zone 1 and 2 are 784 m^3 each while Zone 3 is 2172 m^3. Atrium glazed façade consists of a 204 m^2 area.

Overall U-value for exterior facing walls is 0.23 W m^{-2} K^{-1}. Roof U-value is 0.24 W m^{-2} K^{-1}. Windows are double glazed units having overall U-value of 1.7 W $m^{-2}K^{-1}$ and g-value of 0.6. Atrium glazing U and g-values are 1.8 W $m^{-2}K^{-1}$ and 0.63 respectively. Zone 1 is air conditioned all year round: set point temperatures are 20°C and 26°C for heating and cooling seasons respectively. Zone 2 shares the same limits on allowable temperatures but it is decided to run HVAC equipment accordingly to the expected occupancy period from 7 to 20, starting one hour before considered occupancy starts. Nevertheless, 16°C is the minimum allowable set-back temperature. Zone 3, which stands for the central atrium, is heated during winter, resorting to sun shading and night time ventilation for temperature control in summer.

It is assumed that summer period spans the year from April to August. Winter period encompasses the rest of the year. Zones occupancy is assumed to vary accordingly to the picture that follows:

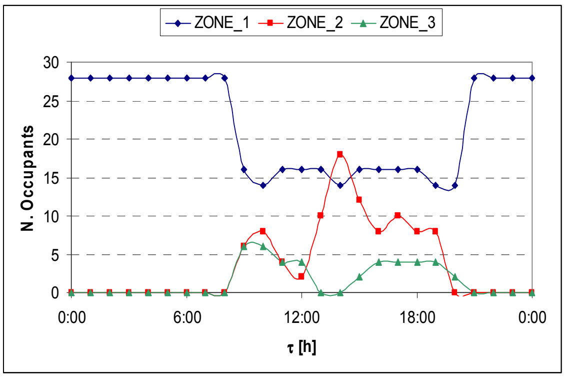

Figure 3. Profiles for the supposed occupancy of the three zones the building is organized in.

DISCUSSION

Air flow through building spaces originates from pressure distribution around and within the building itself. Pressure distribution is due to the combined effects of wind, thermal buoyancy (namely stack effect) and mechanical ventilation if any. Although natural ventilation is acknowledged as being an affordable and low energy way for improving indoor air quality, factors involved in natural ventilation cannot be evaluated with acceptable accuracy in most of the cases. Stack effect is caused by the density gradient resulting from the temperature difference between indoor and outdoor air. Wind contribution can be written in the form of pressure coefficients, which are of difficult determination. Moreover, the lack of control mechanisms on ventilation rates has often caused natural ventilation to be dropped. Hybrid ventilation, which integrates both natural and mechanical systems, can meet ventilation objectives by varying the operating mode depending on the time of the day or the season of the year (Heiselberg, 2002, Turner 2007). In this paper two ways of operating ventilation are investigated. The primary principle guiding the design is to provide patients with the most comfortable conditions. Then, the secondary objective is to couple this requirement to the minimizing the energy input required for heating and cooling the building as a whole, taking special care of the central glazed atrium since buildings with large atria often present unresolved problems related to air conditioning and contaminant spreading.

The design phase moves its steps from determining the outdoor air rate that is to be supplied to the hospitalization area and the threshold level admissible for indoor contaminants. Assuming an occupancy of four people per room and taking into consideration emissions from a low polluting environment, the supply of outdoor air set to 55 $m^3 h^{-1}$ per person, a value that is consistent with the EN 13779 recommendations for having an IDA 1 indoor air quality (CEN, 2004). It is stated that maximum allowable CO_2 level for the whole building is 1000 ppm. During winter season the whole system relies on mechanical ventilation. Zone 1 is ventilated during all the day with 1540 $m^3 h^{-1}$ of outdoor air. Zone 2 is supplied with the same amount of fresh air from 7 to 20. There is no recirculation. The equipment consists of a large air handling unit with maximum airflow rate of 3080 $m^3 h^{-1}$ and two heat recovery units coupled in series, whose overall efficiency is set to 0.8. The system is planned to take advantage of exhaust air to preheat fresh air that is blown in the atrium. Then air flows up through the atrium to occupied spaces and then out. In order to avoid atrium overheating, the system is intended to by pass heat recovery as atrium air exceeds 21°C. In summer the system is planned to rely partially on natural ventilation. Zone 1 and Zone 2 are supposed to be mechanically ventilated with 1540 $m^3 h^{-1}$ of outdoor air from 7 to 20. During night time, a regulation algorithm is planned to operate a motorized window system. If outdoor temperature is higher than 18°C, air is let flow into the building as long as air temperature in Zone 2 falls below 23°C. To exert a control on airflow entering their rooms, patients spaces are equipped with self regulating hygroscopic vents. They are devices that allow airflow depending on the sensed value of relative humidity. They are equipped with a damper in order to allow one way flow only. They are intended to let air flow from atrium into rooms and then out, while they have zero flow in the opposite direction.

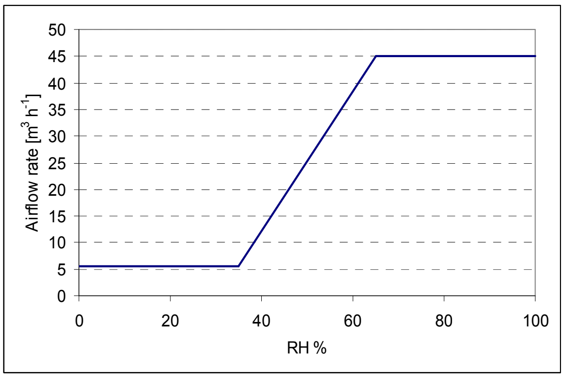

Figure 4. Relationship between RH and airflow rate given for the self regulating vents taken into account in the present study for a pressure drop of 10 Pa.

CONTAM is not provided with sensors reporting relative humidity directly. The following algorithm has been translated into the software control logic. Humidity ratio (x) is calculated as follows:

$$x = \frac{MF_{H_2O}}{\left(1 - MF_{H_2O}\right)} \tag{1}$$

where MF_{H20} stands for water vapor mass fraction, i.e. the ratio of the mass of water vapor to that of moist air. Relative humidity can be written as:

$$x = 0.622 \frac{\varphi \cdot p_{sat}}{\left(p_0 - p_{sat} \cdot \varphi\right)} \rightarrow \varphi = \frac{MF_{H_2O} \cdot p_0}{p_{sat} \cdot \left(0.622 + 0.378 \cdot MF_{H_2O}\right)} \tag{2}$$

where p_0 is ambient pressure and p_{sat} is water vapor saturation pressure. The saturation pressure of water vapor in air varies with temperature accordingly to:

$$p_{sat} = e^{\left(77.345 + 0.0057 \cdot T - \frac{7235}{T}\right)} \cdot T^{-8.2} \tag{3}$$

where T stands for air absolute temperature [K]. As exponential functions are not implemented in CONTAM, the expression for saturation pressure has been approximated to give:

$$P_{sat} = 0.0502 \cdot t^3 + 0.9325 \cdot t^2 + 47.5660 \cdot t + 605.1 \tag{4}$$

Each room is equipped with 4 intake and 4 exhaust vents. As their performance is also influenced by the pressure drop across them, it is decided to simulate fan off conditions with a total airflow of 150 $m^3 h^{-1}$ entering Zone 2. Rooms are also provided with a CO_2 sensor in a such way that, if hour by hour CO_2 concentration exceeds 1000 ppm, mechanical ventilation is turned on.

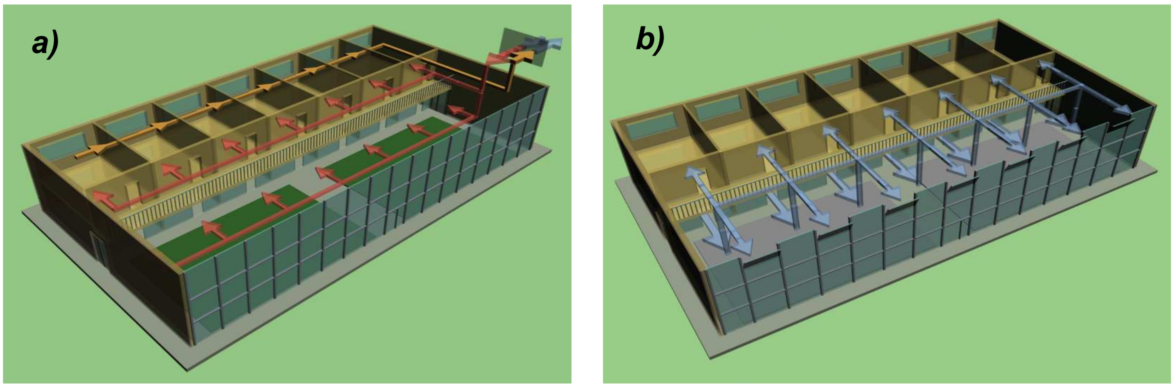

Figure 5. Air distribution details: winter (a) and summer (b) operation.

RESULTS

The integration of the TRNSYS building model and the CONTAM airflow model represents the most challenging feature of the project. As nodes are assigned to each zone and as nodes are linked each other by any mean that enables air flow, the flow of air through any given path is a function of the pressure difference acting on either side of the path. In the present paper wind contribution is always neglected therefore pressure differences are only due to thermal buoyancy and HVAC equipment. The stack effect is produced by density differences due the variation in temperature between adjacent zones. The other way round, zone temperatures are function of airflow entering zones themselves. It follows that heat transport and ventilation phenomena are influenced by each other. Two approaches are available when coupling thermal and airflow simulation models: the "ping-pong" and the "onion" techniques [Hensen, 1995]. The former states that each model relies on the outputs calculated by the other at the previous time step. In the present study the "onion" method is used, for which the flow rates are handled from the ventilation model to the thermal model, and then air temperatures are passed back from the thermal model to the ventilation model. This process is repeated until zone temperatures changed by less than a defined tolerated amount (0.01 K). The following pictures report the annual profile for air temperatures for all the three zones the building is divided in. CO_2 concentration for a standard operation day is also displayed. Each zone was set to having an initial temperature of 20°C. Default ambient CO_2 concentration is 350 ppm. Summer dehumidification is not performed. Comparison is shown between the results that are attained by the means of the hybrid ventilation system discussed above (HYBR) and what could have resulted if winter mechanical ventilation strategy is extended to the whole year (MECH).

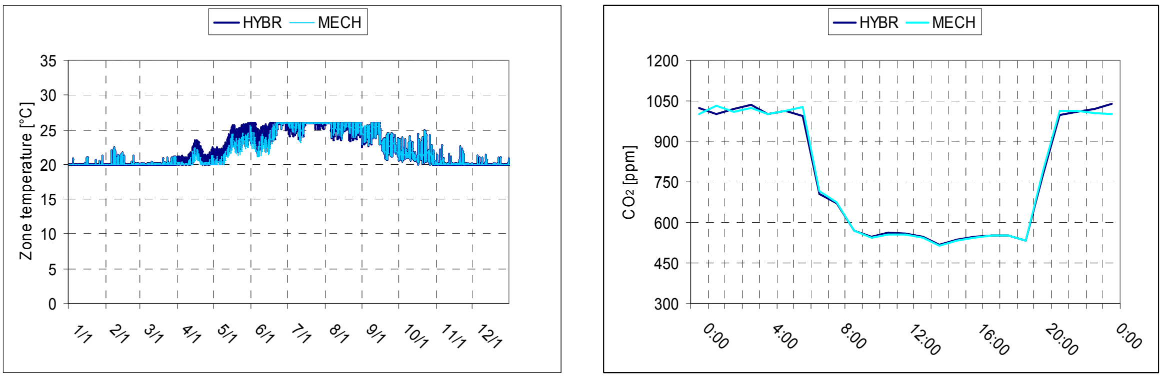

Figure 5. Air temperature and CO_2 concentration profiles referred to Zone 1 for the whole year and for a standard operation summer day respectively.

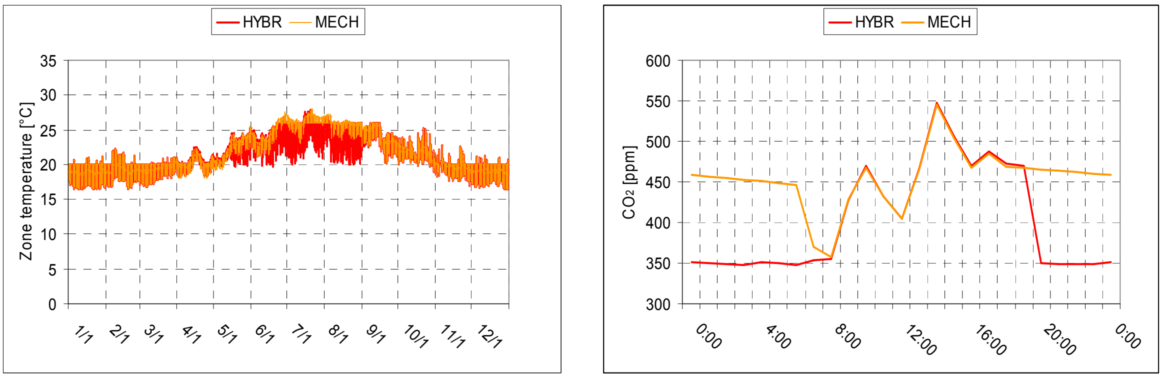

Figure 6. Air temperature and CO_2 concentration profiles referred to Zone 2 for the whole year and for a standard operation summer day respectively.

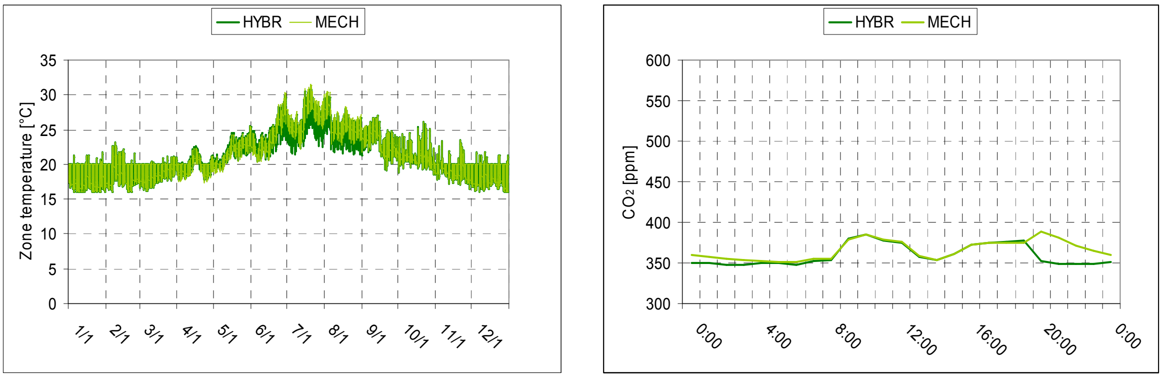

Figure 7. Air temperature and CO_2 concentration profiles referred to Zone 3 for the whole year and for a standard operation summer day respectively.

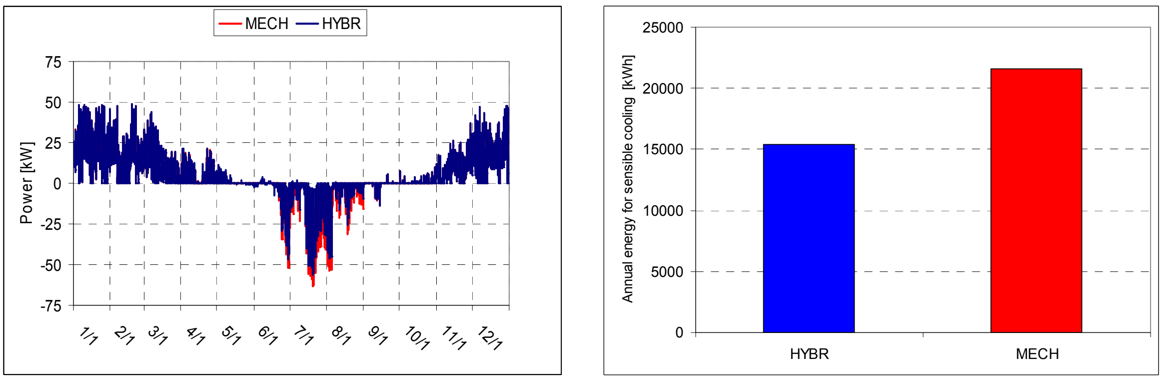

Figure 8. Annual loads (positive values stand for heating demand, negative values represent sensible cooling needs) and annual cooling energy for the investigated building.

CONCLUSIONS

Analysis suggests that good indoor air quality is attainable without compromising overall building energy performance. During winter, making use of the supply air rate to the hospitalization area for atrium heating is found to be of help in reducing the heating needs of the large central glazed area. In summer, results suggest the strength of the integration between architectural and technological aspects. Sunshade provides considerable results in avoiding central atrium over heating. Natural ventilation has proved to be effective in temperature control, as Zone 2 and 3 temperatures remain within tolerable ranges: 30°C in the atrium are exceeded for only 30 hours. The system is capable of keeping CO_2 concentration within admissible ranges. Natural ventilation airflows entering the building during night time are considerable: the concern for trying to avoid patients being exposed to excessive draughts results in the adoption of self regulating vents. Even if they are probably less effective than windows opening, their contribution in keeping the hospitalization area consistent with good indoor air quality is not negligible. During the assumed summer period and the corresponding nocturnal operational schedule, natural ventilation is capable of maintaining the CO_2 concentration within the hospitalization area below the threshold value of 1000 ppm for about one quarter of the total time.

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