Natural and Hybrid Systems for the Ventilation and the Air Conditioning of a University Complex

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ABSTRACT

The main features of a preliminary HVAC system project relative to a university complex is presented. The project philosophy follows the principles of sustainability, whose guidelines are based on the saving of energy resources, on high environmental quality standards and on the man-building relationship.

A strong integration with the city territorial system has been identified as a key issue in the early design stage. A cogeneration power plant, linked to a district heating network, has been selected to supply thermal and electric energy to the university complex.

Emphasis has been placed on the definition of the plants requirements for each building type, according to the destination uses, and to the development of solutions compatible with low-energy strategies. Hybrid and natural ventilation has been proposed to this aim. The suitable architectural designs for didactic area, including classrooms, library and administrative services, and for departments area, hosting offices and research laboratories, are exemplified.

1. INTRODUCTION

This paper discusses the approach followed in the preliminary design of the HVAC systems for a university complex to be built in the Turin suburbs; this project implies the relocation of the scientific faculties and departments of the University of Turin, now mostly situated in the urban centre.

The complex extends over a surface of 360,000 m^2, on which the buildings hosting the teaching and research activities of the 13 departments of the scientific faculties will be erected. Didactic spaces include lecture halls, libraries, teaching laboratories, services and administrative offices, while in the research area mainly offices and laboratories will be located. The complex will consist of 14 buildings, variable in height from 1 to 4 levels, each of them constituted of several modules of unitary length around 50 meters, with width ranging from 11 to 25 m. Service joints connect the modules to form buildings of varying length from 150 to 250 meters, summing up a floor surface of about 120,000m^2. The buildings are inserted in the area leaving ample spaces devoted to green, to form an enjoyable public urban park.

The HVAC system project has addressed two main issues. The first one is the definition of the design requirements for the various buildings, according to the destination (offices, research laboratories, classrooms, didactic laboratories, libraries, etc.) and to the integration of the plants into the building complex. In this phase, emphasys has been placed on the definition of design solutions for the building-plant system aimed at the exploitation of renewable energy sources and on the reduction of the environmental impact.

The second issue relates to the selection of plants at the territorial scale, i.e. the definition of centralised power plants (production of hot and refrigerated water, combined heat and power production, etc.) and the layout of the energy distribution networks. Particular attention has been devoted to the integration of the energy system with factors such as the urban transportation systems, the vehicular and pedestrian road networks, the plani-volumetrical distribution of the buildings, and the design of green areas.

The project has been developed in close cooperation with the architectural/urban planning design team, taking into account the experience gained in the past by Turin University and by other university and research institutes.

The project philosophy is based on the principles of sustainability, whose guidelines are based on the saving of energy resources, on high environmental quality standards and on the man-building relationship. The project is part of a trend of accomplishments, of which the most significant examples can be found in Northern Europe (The Netherlands, Scandinavia, Great Britain), where relevant attention is paid to the use of materials and building technologies compatible with the environment, to the research of high performances for the building envelope, to the climatic/territorial integration of the buildings, to the rational exploitation of energy and the use of renewable sources.

A thorough campaign to acquire and process meteorological data for the site was carried out in order to define the specific characteristics of the climate, so that the project could be fully integrated with the environment.

2. MAIN FEATURES OF THE PROJECT

The main design requirements for the internal environment have been defined with reference to thermal comfort, indoor air quality, natural and artificial lighting, room acoustic quality and sound insulation requirements. Other fundamental requirements that have been considered are safety (fire prevention, risks connected to the use of dangerous substances, risks of biological contamination, etc.), plant easy maintenance, and high flexibility in relation to the use of the buildings.

While developing the architectural project, some important decisions were taken related to the HVAC systems to be adopted to meet the environmental quality requirements. The system design can in fact be based upon two different approaches:

- a first approach, which can be briefly defined as “traditional”, based upon the general use of mechanical air-conditioning; such systems mainly use electricity and fossil fuels as primary energy inputs, in a “direct” way or by employing a co-generation and district heating plant.
- an “alternative” approach that privileges the exploitation of renewable energy sources, for example by adopting architectural design solutions allowing for natural ventilation and cooling, the exploitation of solar radiation for thermal and lighting purposes, etc.

The two above-mentioned approaches are not necessarily mutually exclusive: one can think of intermediate solutions between the two extremes or of differentiated solutions according to the characteristics and destinations of the buildings: for example, traditional plant engineering is necessary for those spaces, such as laboratories, with demanding requirements for safety and air quality control because of the use of toxic or dangerous substances, while the alternative approach is most suited for spaces such as offices and classrooms.

Such approach has influenced the design choices relating to:

- plani-volumetrical features of the buildings (position, size and orientation of the buildings, definition of respect areas, etc.);
- internal layout of the rooms (possibility of natural ventilation, exploitation of natural light and free solar gain, protection against external noise sources, etc.);
- choice of building materials and construction of the walls;
- definition of performance requirements and design conditions for the plant systems.

Particular attention has been paid to the selection of highly efficient HVAC and control system components, and to solutions for the building envelope (increase of thermal inertia and insulation, control of summer solar heat gains, etc.) in order to limit the peak HVAC system cooling load.

Environmental and plant requirements have been summarised in files relative to each type of space (e.g., chemical laboratory, office, classroom, etc.). The design data have been defined with reference to the technical standards and to the laws currently in force in Italy.

3. CLIMATIC CHARACTERIZATION OF THE SITE

The buildings location phase was preceded by a weather data acquisition and processing campaign in order to define the climatic characteristics of the site and to identify potentially usable energy resources.

A statistical processing has been carried out for each climatic quantity so that the available sample could be made significant.

3.1 Wind

The windiness of the site is characterised by a velocity distribution with a moderate average and a similarly modest dispersion. There are occasional episodes of high intensity that do not appear to be linked to seasonal events.

The wind direction is markedly stationary. Maximum intensity values are typically not associated with the prevailing direction, but they present a clear dispersion, with some grouping of values in the 280-320° direction.

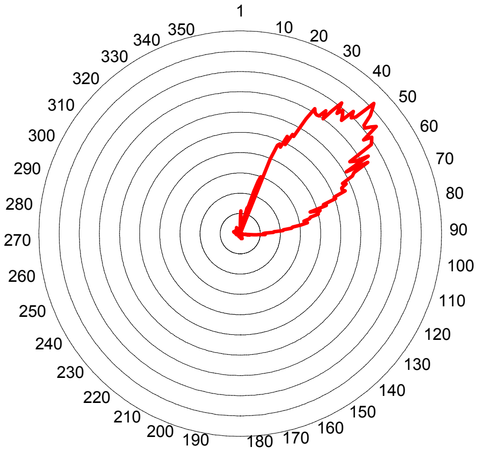

Figure 1 – Wind Direction Frequencies

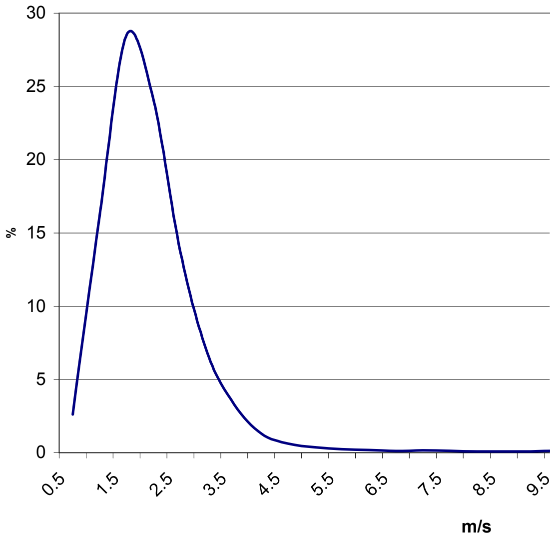

Figure 2 – Wind Speed Probability Distribution

3.2 Temperature, Humidity and Solar Irradiance

Winter irradiance is very unstable, while the summer energy output is remarkable. Temperature and humidity trends outline a temperate climate characterized by modest thermal ranges and by high humidity.

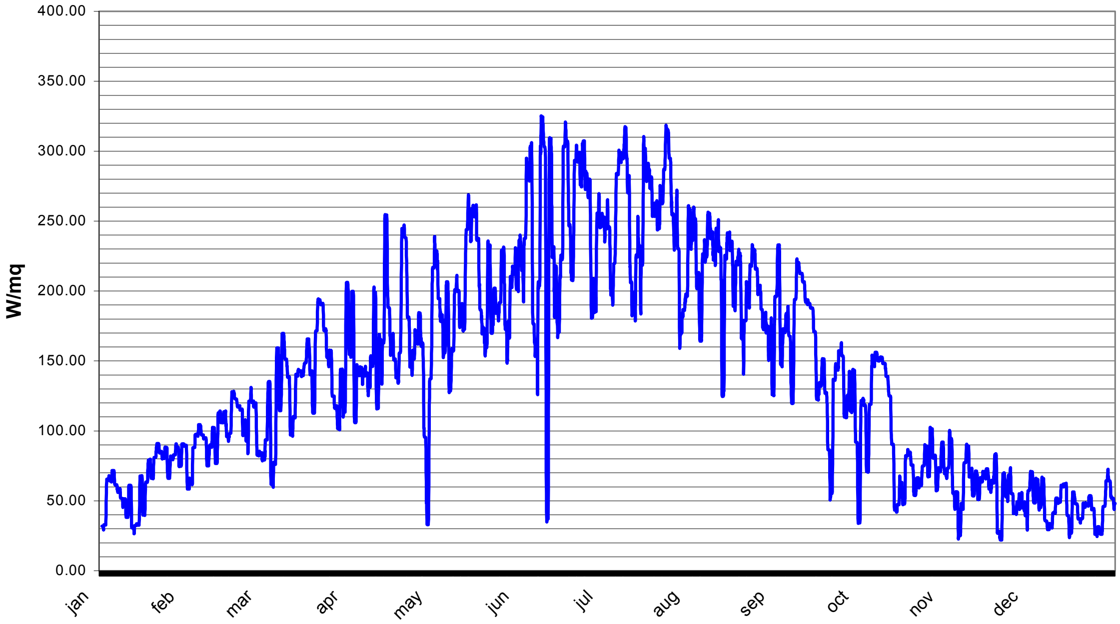

Figure 3 – Daily Average Global Irradiance

4. CENTRAL POWER PLANTS AND PRIMARY FLUID DISTRIBUTION NETWORKS

A strong integration with the city territorial system has been identified as a key issue in the early design stage.

A cogeneration power plant, linked to a district heating network, has been selected to supply thermal and electric energy to the university complex. Hot water at 90° maximum temperature will be distributed through an ample underground technological tunnel, that will also host the other main fluid and electric power distribution networks and through which small electrical vehicles will be able to run for maintenance (Figure 4).

Each building will be provided with an independent hot water distribution network, connected to the main district heating network through a heat exchanger. This solution allows flexibility in system management and is fully compatible with future construction developments. 16 zones for 16 related heat exchangers have been envisaged, on the basis of the planned building volumes. Each heat exchanger (having a thermal power rating between 300 and 1,400 kW, for a total power of about 12 MW) will be installed in the buildings basement and will be fed through the technical tunnel.

A centralised chilled water production with absorption machines fed with district heating water has not been considered for the following main reasons:

- low temperature of supplied water which implies a low COP;
- during the summer, thermal power will be sufficient for service water heating only;
- high costs.

Consequently, chilled water will be locally produced with conventional, electrically driven vapour compression machines: one chiller will be typically provided for each building.

5. BUILDING-HVAC INTEGRATION

The selection of HVAC systems, control and building integration strategies has been made taking into account the specific requirements of the two main sections that constitute the university complex, i.e. the didactic section (including classrooms and didactic laboratories) and the research section, which can be mainly identified with the department areas (including offices and research laboratories).

The following HVAC system solutions have been selected for the main areas of the complex:

- for classrooms, all-air VAV systems, capable of tracking the highly variable thermal and ventilation loads;
- for the laboratory areas, VAV systems in which the air supply flow rates are controlled according to the number of fume extraction hoods in service, paying attention to the fact that laboratories should always be at a lower pressure with respect to adjacent spaces. Thermal loads will be handled by a low-temperature floor radiant system.

- for the office spaces, low temperature radiant heating and cooling (floor or ceiling mounted), coupled to hybrid ventilation systems with mechanical supply and mechanical / natural extraction.

5.1 Didactic Section

Buildings in the didactic section exhibit an architectural design compatible with low-energy strategies, such as daylighting and hybrid ventilation assisted by low energy fans possibly driven by photovoltaic cells (Figure. 5).

The inner atrium space acts as a light well providing natural lighting to the interior. Ventilation is activated by stack effect: the central atrium accomplishes the function of extraction for the airflows coming from the rooms that lean on it. Automatic opening of skylights by means of thermostatic control is provided to avoid summer overheating of the atrium. The ventilation system can modulate the outdoor air flow rate according to the actual occupation.

Typically the HVAC system will have the following features:

- single duct, all outdoor air VAV system with zonal boxes with reheat coil and modulating damper.
- winter temperature control is achieved by reheating, while flow rate control based on ambient temperature is adopted in summer;
- outdoor air flow rate is controlled by an indoor air quality sensor (minimum flow rate based on ventilation standard);
- heat recovery from exhaust air through a coupled coil heat recuperator (50% minimum efficiency);
- supply air distribution through ceiling-mounted ductwork, preferably on the outdoor facing side of the room, and high induction diffusers;
- air extraction at ceiling level, on the opposite side with respect to air supply, i.e., towards the atrium through grilles. The above described solution achieves a good air displacement of the room, by extracting the pollutants produced by users, and it guarantees a better fire prevention as far as it keeps away fumes from the occupants zone.

5.2 Research Section

In the research section, each building may be divided into two areas having different construction and plant characteristics. The lower block (basement and ground floor) consists of a massive reinforced concrete pillar and slabs structure with masonry walls; the basement includes technical rooms and garages, while the ground floor hosts the laboratories. The second one (first and second floor) comprises the teaching and research staff offices; for this block, a light steel and wood structure is envisaged; floors will be of the slab-deck type without using concrete: for this reason, the radiant panel will not be traditionally built with pipes embedded in the concrete, but with modular plastic components with pre-formed water passages. The distribution of the static load and the thermal uniformity will by guaranteed by a metal plate. This system has the advantage of having a very low inertia and is compatible with the control strategy implying a quick

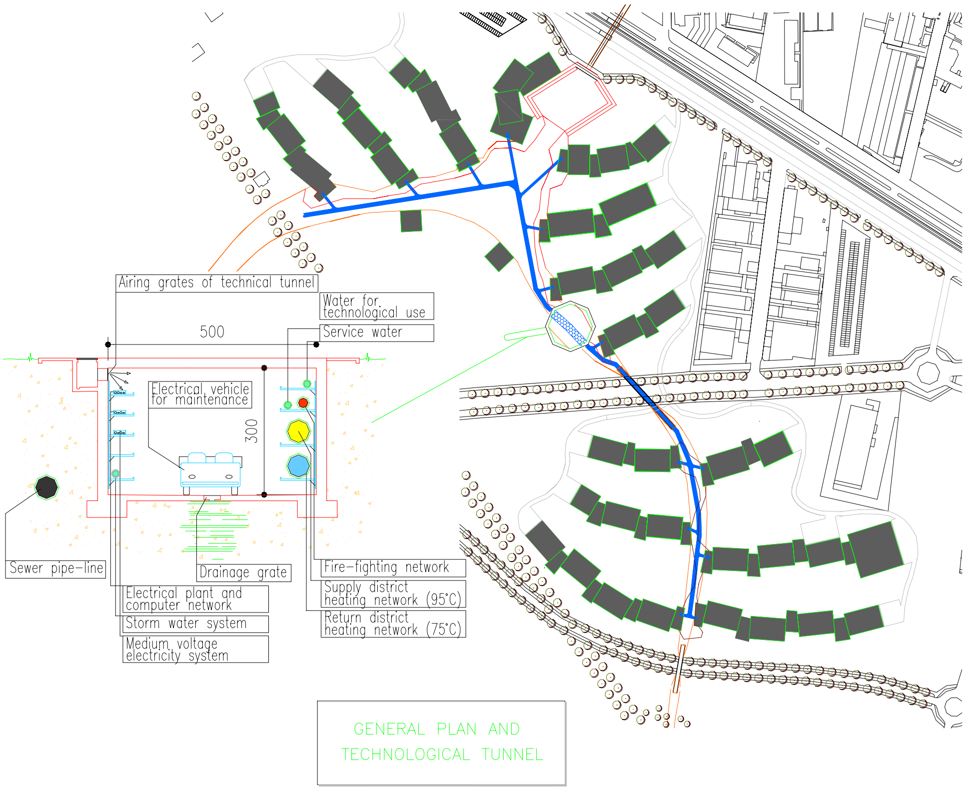

Figure 4 – Technological Tunnel

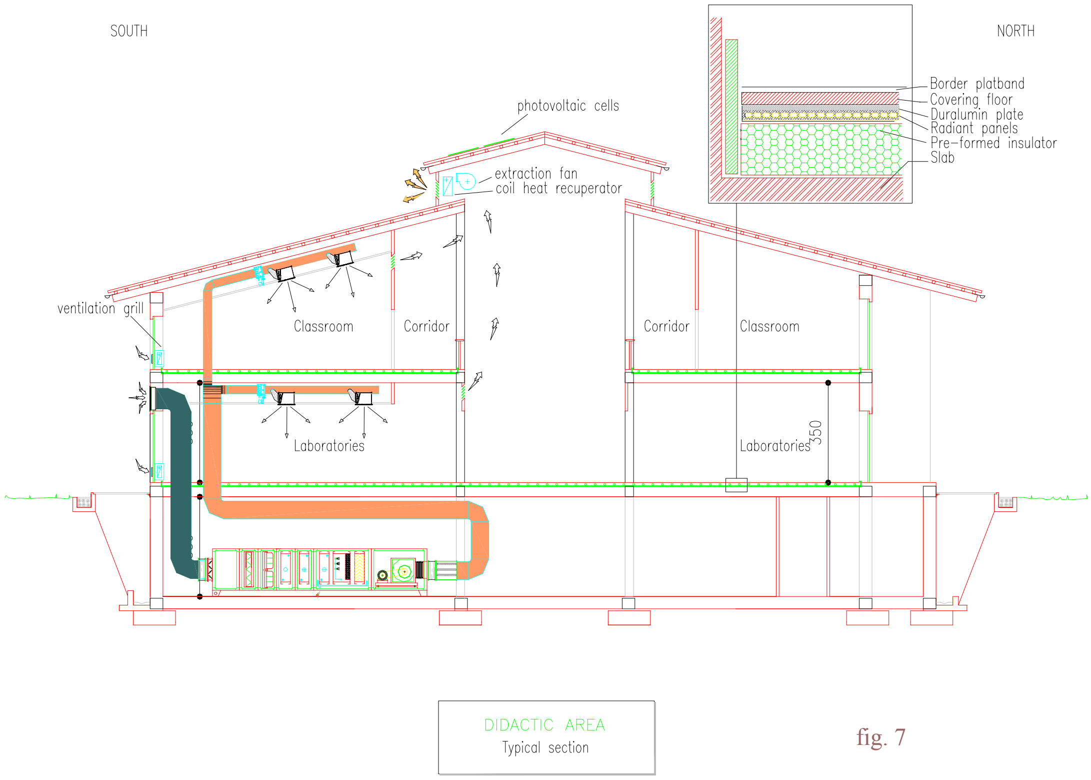

Figure 5 – Section through Didactic Building

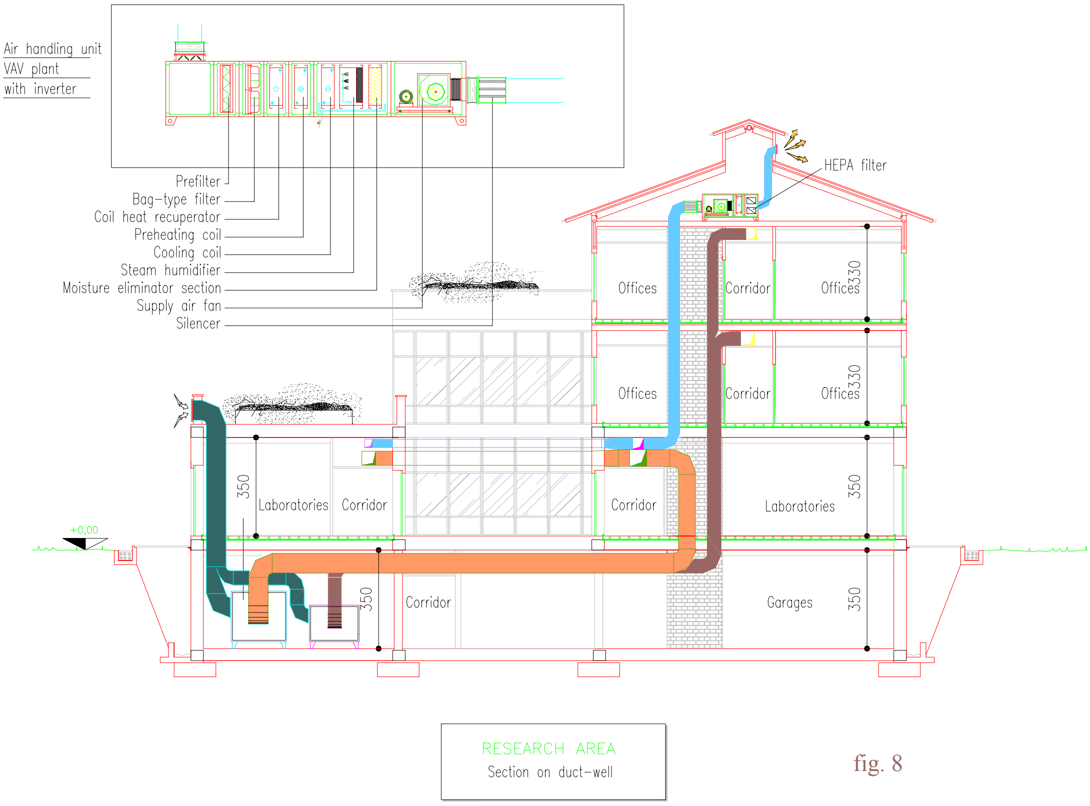

fig. 8

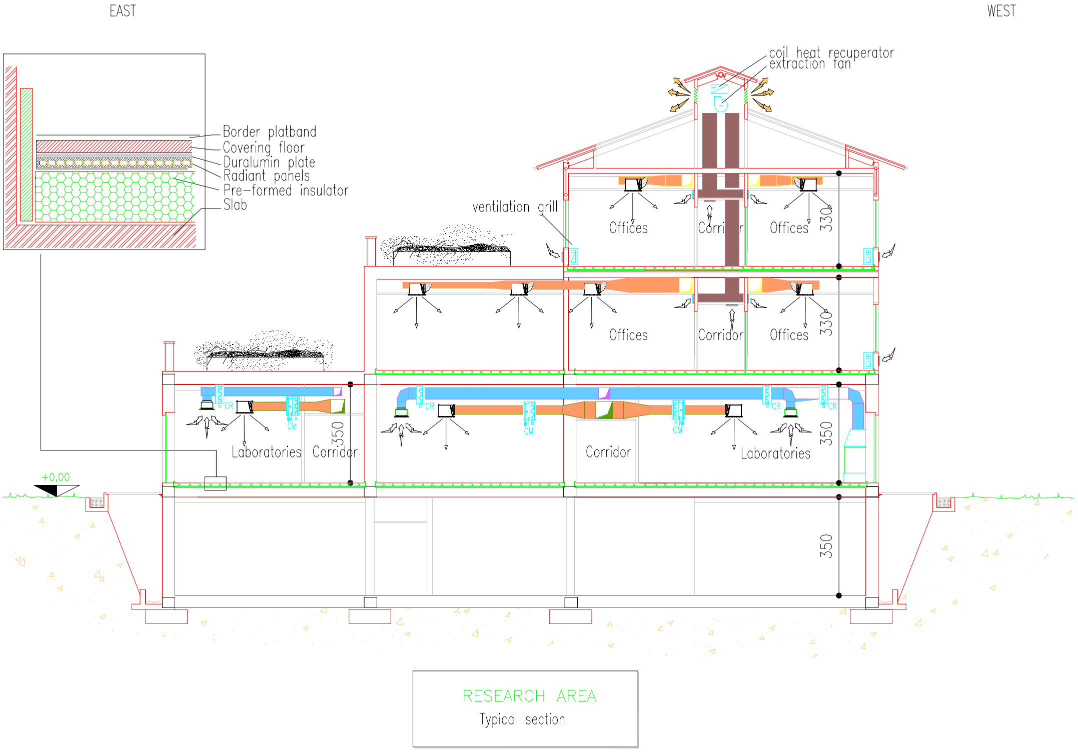

Figure 6 – Sections through Research Building

response of the plant (e.g., the professors can use the office in overtime by activating the plant, thanks to the badge opening the entrance door).

5.3 Laboratories

The schemes in Figure 6 show a plant solution where the technical rooms for the air treatment are placed in the basement.

The outdoor air intake will take place on top of the building (or, alternatively, on the façade at a suitable level) directly or by placing a solar air collector that provides a winter pre-heating of the intake air.

The extraction groups will be placed on top and will be distinct according to the area; care will be taken in avoiding cross contamination with the makeup air.

It will be an outdoor air system (primary air) and will be coupled to a base radiant-type system with floor panels.

The mechanical-controlled ventilation will be based upon a variable supply flow scheme. The air handling unit will take air in with a variable delivery and will depend on the active areas (open area grill); the intake air delivery will be adjusted on the basis of the speed of the extraction cowls.

The regulation of temperature and relative humidity will guarantee independent microclimatic conditions for each room.

The renewal air will be taken from the ceiling into the classrooms and corridors and will be extracted from the laboratories ceiling. Corridors will be kept at positive pressure to avoid cross contamination among the various rooms.

Transit grids will be placed in the floor to clean the premises, particularly from technical gas (mainly heavier than the air). The laboratory areas will be kept at negative pressure to avoid the diffusion of polluting substances in the adjacent rooms.

All laboratories will be provided with manual and/or automatic openings (windows) for emergency ventilation.

5.4 Considerations on Office Ventilation (Natural – Hybrid)

For the ventilation of the offices two alternative proposals have been elaborated. The first one is based on mechanical supply of treated air and hybrid extraction. The second one may operate in three working modes, based on outdoor conditions: natural ventilation, with or without heat recovery, and mechanical ventilation.

For both systems, the extraction is obtained by a hybrid system combining the natural effects of buoyancy, wind pressure and solar gains with the head supplied by a mechanical fan powered by photovoltaic cells. The ventilation system control airchange and indoor humidity, since the sensible thermal load are handled by floor radiant panels, working both in the heating and cooling mode.

5.4.1 Energy Feasibility for the Natural System with heat Recovery

Three operating modes have been defined for the system provided with the heat recovery circuit (Figure 7)

NVR : natural ventilation with heat recovery for $\Delta p > \Delta p_{rec} > \Delta p_{cr}$

NV : natural ventilation without recovery for $\Delta p_{rec} > \Delta p > \Delta p_{cr}$

MV : mechanical ventilation, as in solution 1, for $\Delta p < \Delta p_{cr} < \Delta p_{rec}$

where Δp_{cr} is the minimum pressure head that allows the hygienic air exchange and Δp_{rec} is the minimum pressure head that allows the insertion of the natural ventilation supply air treatment .

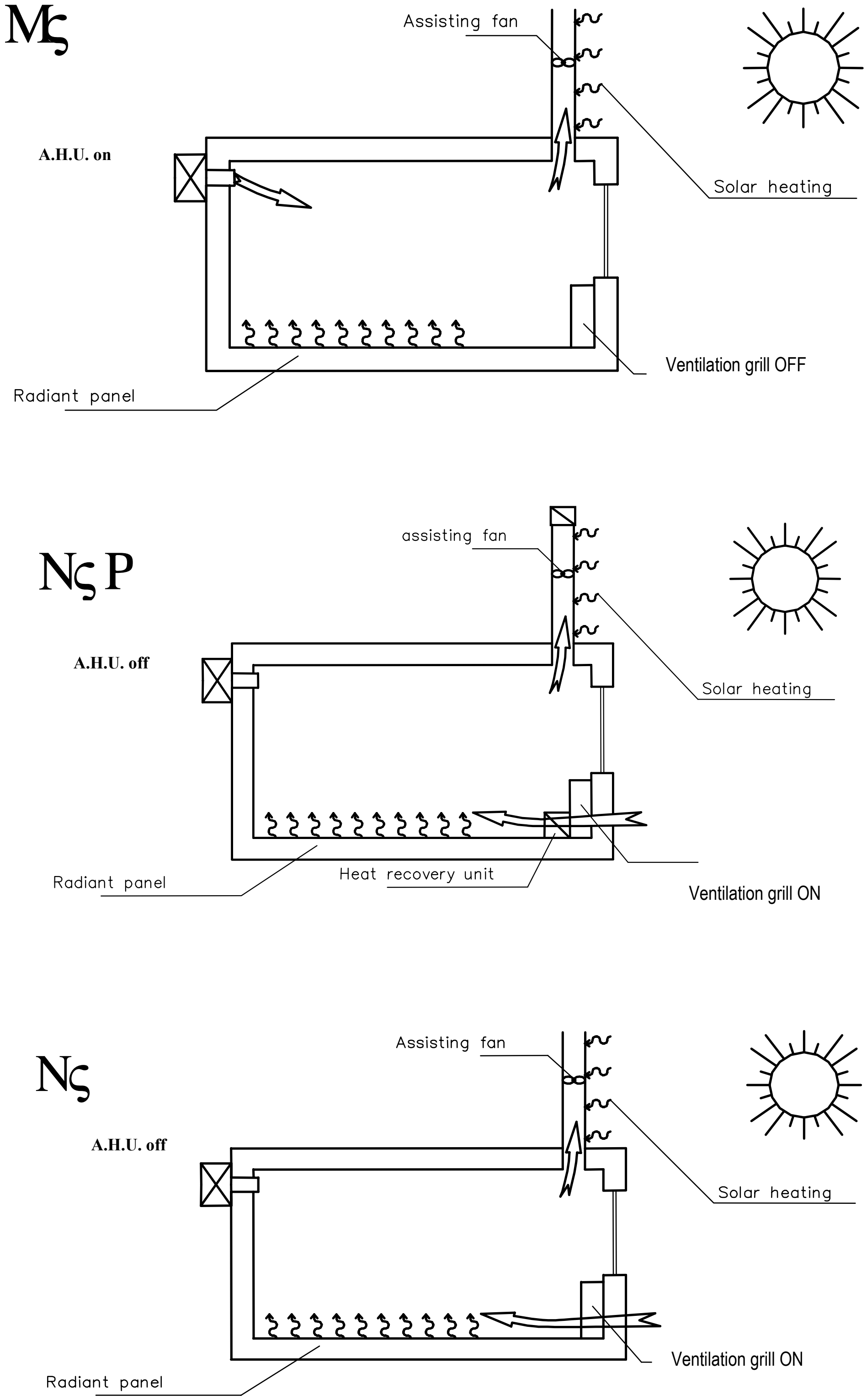

Figure 7 – The three Operating Modes of the Hybrid Ventilation System

The pressure head available in the hybrid mode is given by the sum of the terms associated to the installed systems[1]. For instance, in the offices:

$$\Delta p = \Delta p_{buoyancy} + \Delta p_{wind} + \Delta p_{solar} + \Delta p_{fan} \qquad (1)$$

where “buoyancy, wind, solar” refer to the natural actions, and with “fan” the presence of a fan assisting the outflow is considered.

Each term of the sum (with the exception of the auxiliary fan head) is evaluated on a statistical base (Fracastoro 2000) through the knowledge of the TRY (Test Reference Year), a set of weather data obtained by making an average of five-years records at our disposal, a brief description of which was given in paragraph 3.

For example, the pressure head that can be obtained by the stack effect depends on the temperature difference between the air outside and inside the building: the first step is the definition of T_{cr}, external temperature to which corresponds Δp_{cr}, a minimum pressure head value necessary to obtain the air exchanges fixed by the standards. This value is different for each architectural and plant layout (chimney dimension and type). T_{cr} is compared with the average trend of the temperature recorded on the settlement site and this allows to make an estimate of the annual energy consumption of the system.

The pressure head that can be obtained through the stack effect can be estimated by:

$$\Delta p_{buoyancy} = \frac{g\rho \Delta H (T_i - T_e)}{T_m} \qquad (2)$$

where ΔH is the vertical quote between lower and upper openings; g represents the gravity acceleration; ρ is the mean air density; T_i and T_e the internal and external temperature and T_m the average between T_i and T_e.

This, associated to the value of air exchange established by the law, and to a flow law:

$$Q = c_d A \sqrt{\frac{2\Delta p}{\rho}} \qquad (3)$$

where Q = volumetric flowrate, yields the external T_{cr} .

By inserting the meteorological temperature data, the hourly pressure head values are calculated. A diagram of the hourly frequencies is processed per intervals of available head (Figure 8); the overcomings on the critical prevalence during the annual cycle are counted and the information used for a first feasibility evaluation of the project. Knowing the typical energy consumption of a conventional air handling unit, applicable in such offices, and considering the estimated losses, it is possible to determine the electric energy savings, in comparison to the entirely mechanical strategy. This is transformed in monetary cost through the knowledge of the electrical supply tariff. Therefore we can compare the additional costs of installation and maintenance to the savings, and foresee a time of return of the investment.

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[1] The assumption is made that the principle of superposition of the effects is applicable. This is certainly an approximation (for instance the pressure head provided by solar heating in the extraction duct is a function of the exhaust air speed, which depends on the total head) that is however acceptable at this stage of the design process.

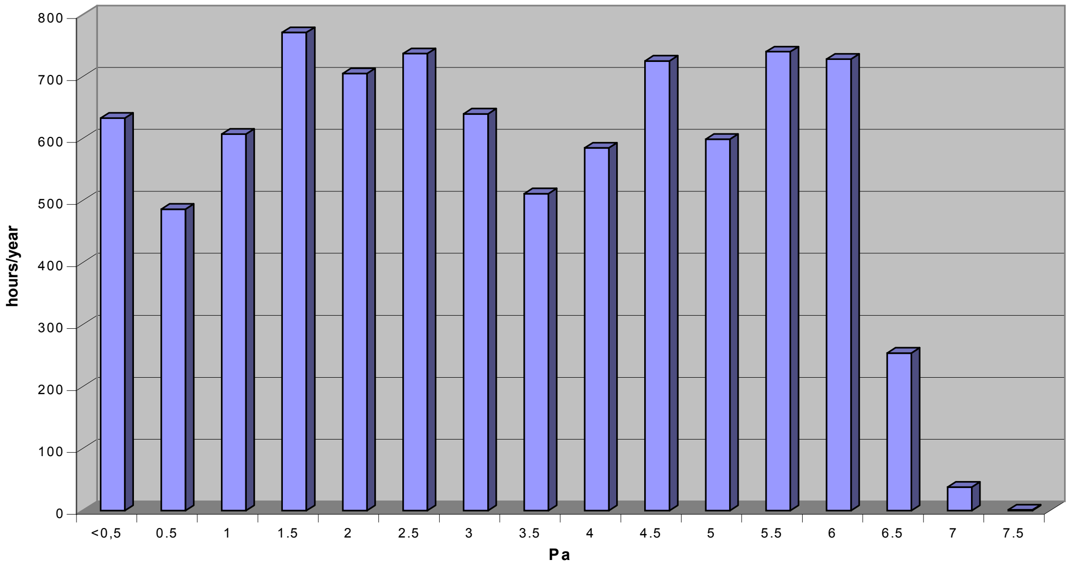

Figure 8 – Pressure Difference Frequencies without Solar Chimney

5.4.2 Technical Feasibility

The flow can be described by two principal quantities: speed and temperature. Speed control can be easily accomplished by means of automatic controlled natural airing devices available on the market. Temperature control instead is not easily achieved with a natural ventilation system and, while it is relatively easy to conceive a conceptual solution, it is not easy to retrieve data to support performance and cost evaluations.

Two solutions for air preheating have been evaluated. The first one uses air heating coils, fed by the same hot water network used by the radiant panels, while the second is a low speed heat recovery system with intermediary fluid.

A crucial parameter in the use of heat recovery with natural ventilation is the pressure loss. The natural ventilation systems must provide enough static pressure difference to win the pressure losses and to guarantee a significant heat recovery. Systems based on such concept have been already studied, proving the feasibility of the concept and getting mathematical laws that describe their operation. S.B.Riffat and G.Gan (Riffat and Gan 1997), for instance, derived with a CFD code the following equations for the pressure loss coefficient k:

$$k = \frac{\Delta p_{loss}}{0.5\rho V^2}$$

$$k = (2.6 + 1.77n)V^{-0.03n^{3/4}} \qquad (4)$$

where Δp_{loss} represents the loss of static pressure through the unit (Pa), V the average speed (m/s) and ρ the air density (kg/m^3), n the number of heat recovery units installed (e.g., n = 2 in the case of a coupled coil heat recuperator).

Through this equation one can estimate the minimum head needed to win the pressure loss across the heat recovery coils , versus the flow mean speed. The recommended speed in this case is 0.5 m/s, above which the pressure loss becomes too high for a typical natural ventilation system. Under such hypotheses, a minimum value of 1 Pa for Δp_{loss} is obtained. This should be added, together with the other losses, to the pressure head needed to achieve the hygienic air change (Δp_{cr}).

$$\Delta p_{rec} = \Delta p_{cr} + \Delta p_{loss}$$

Through approximate calculations one can estimate this term at around 1.2 Pa, for a chimney serving 10 offices (always paying attention that the air speed should not exceed 0.5 m/s), and therefore a total demand in mode NVR of around 2.2 Pa. In mode NV a pressure head of 1.2 Pa will obviously suffice.

5.4.3 Preliminary Evaluation of the Achievable Saving

A typical building of this project requires around 15,500 m^3/h of renewal air, for the office spaces only. Usually, to this aim two air handling units available on the market would be installed, for a total electrical power absorption of around 4.5 kW. The system based on stack effect should guarantee the necessary ventilation for around 7,641 hours during a typical year of operation; the corresponding electric energy consumption would therefore be equal to 7,034*4.5= 31,653 kWh. Estimating a typical electricity cost of 0.10 EUR/kWh (1 EUR = 0.9 USD), EUR 3,440 could be saved yearly by each department.
Extending the analysis to the whole campus, around 102,000 m^3/h of air would be needed: this requires 13 air handling units (8000 m^3/h flow rate each). The total absorbed power is around 30 kW, which gives an annual saving of around 211 MWh, corresponding to EUR 21,100.

5.4.4 Solar Chimney

The possibility to improve the ventilation by exposing the ducts to the solar rays was studied, that is by adopting the so-called "solar chimneys". The model developed by Sandberg (Sandberg 1999), valid for completely developed turbulent flow, was adopted in the analysis. The average outflow speed can be described by:

$$U = \left(\frac{\alpha B}{\psi} \right)^{\frac{1}{3}} \tag{5}$$

where

$$\psi = \frac{A}{H} \left\{ \lambda_{fric} \frac{H}{D} + \frac{1}{2} \left[(1 + k_{in}) \left(\frac{A}{A_{in}} \right)^2 + \left(\frac{A}{A_{out}} \right)^2 \right] \right\} \tag{6}$$

$$B = \frac{g \beta q}{\rho C} \tag{7}$$

B is the *specific buoyancy flux* , as defined by Sandberg; A,H,D stand for: area [m^2], height, width [m] of the duct; λ_{fric} is the friction coefficient and β is the air volume coefficient of expansion.

As it can be noticed, the formula refers to a section of rectangular duct, which allows to expose to solar radiation a larger surface and can be more easily integrated in the roof structure or in a vertical wall, in the case of offices at the lower floor. The heat recovery system and the auxiliary fan are installed in the outlet sections.

The results of the analysis of natural ventilation assisted by the solar chimney are given in Figure 9.

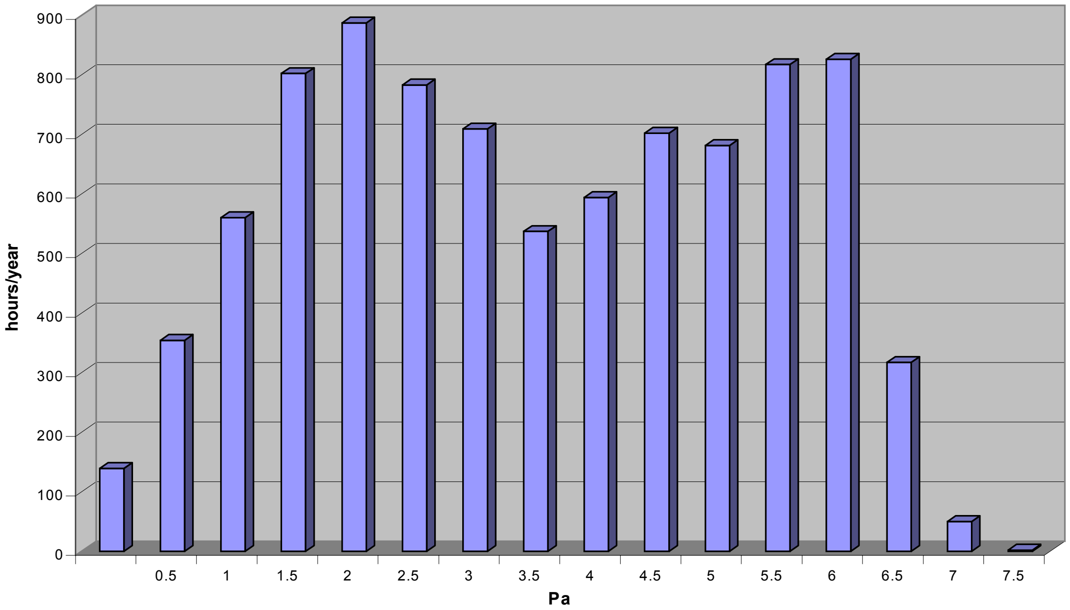

Figure 9 – Pressure Difference Frequencies with Solar Chimney

6. CONCLUSIONS

The summer climatic conditions at our latitudes are characterized by relatively high external temperatures and relative humidity. Besides, neither the daily thermal excursions are very ample, nor dominant wind of significantly intensity are present.

Consequently, natural ventilation allows a limited free cooling of the building, as long as the outdoor temperature is less then the indoor temperature, above which air renewal for only IAQ control (moreover with difficulties in activating the stack effect, which must be improved by solar heating) is possible.

Furthermore, the dehumidification through the introduction of external air is possible as long as the outdoor specific humidity is lower than the inside one (a situation that is normally fulfilled for the classrooms in which most of the endogenous latent load is due to occupancy). Above such conditions the natural ventilation must be integrated with a mechanical humidity control system.

Besides, the nightime cooling of the structure is effective only in presence of significant daily thermal excursions which occur in certain periods of the year only.

Likewise winter climatic conditions are rather severe, and even exploiting at the most the positive effects of the solar gains through the glazed components, of the endogenous heat provided by the occupants (a meaningful effect for the classrooms) and by the electric equipments, it is necessary to provide a backup heating through hot water coils.

A general conclusion that can be drawn is that, for the climatic condition existing in this area, any passive heating or cooling system must be supplemented by some sort of mechanical HVAC plant.

The integrated hybrid climatisation system that has been envisaged has however some fairly innovative features and can allow significant energy savings by adopting, for example, solutions such as:

- Hybrid natural / mechanical ventilation;

- Heat recovery systems;
- Variable air volume HVAC systems;
- Low temperature radiant floor heating and cooling, with low inertia for optimal control.

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