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POTENTIAL OF ACTIVE CHILLED BEAM SYSTEM TO IMPROVE ENERGY BEHAVIOUR AND THERMAL COMFORT IN GLAZED BUILDINGS

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New buildings should provide a high-quality interior environment with the least energy consumption in order to reach the 2020-target set by the European Council. The following research has been developed in a glazed office building located in a typical Mediterranean climate. Firstly, the most energy-efficient heating, ventilation and air conditioning system (HVAC) was chosen and applied to the building case study. Then, the system was sized according to the building's function, construction technology and external environment. Finally, the indoor thermal comfort in a typical storey plan was evaluated through computational fluid dynamics (CFD) simulations assessing indoor air temperature and velocity, age of air and indexes of thermal comfort included in the UNE-EN ISO 7730 standard.

Results show that the active chilled beam system (ACB) is the HVAC-system that guarantees the highest energy-saving. An external air handling unit (AHU) provides primary air which passes through the ACB at a high velocity thanks to nozzles. The renovation air is discharged in the zone once mixed with the induced room air that cools down as it passes through the ACB's cooling coil. Indoor air temperature is always inside the comfort boundaries and its spatial distribution profile close to the ideal one.

Keywords: *HVAC system; active chilled beam; energy-saving; indoor thermal comfort*

POTENCIAL DEL SISTEMA DE VIGA FRÍA ACTIVA PARA MEJORAR EL COMPORTAMIENTO ENERGÉTICO Y EL CONFORT TÉRMICO EN EDIFICIOS ACRISTALADOS

Los nuevos edificios deberían proporcionar un ambiente interior de alta calidad con el menor consumo de energía para alcanzar el objetivo de 2020 del Consejo Europeo. La investigación siguiente se desarrolla en un edificio de oficinas acristalado ubicado en clima mediterráneo. En primer lugar se selecciona el sistema de calefacción, ventilación y aire acondicionado (HVAC) con mayor eficiencia energética. Después, se dimensiona de acuerdo con el uso del edificio, la tecnología de construcción y las condiciones ambientales. Finalmente, se analiza el confort térmico interior en una planta de distribución típica mediante simulaciones de dinámica de fluidos computacional (CFD), evaluando la temperatura, la velocidad y la edad del aire interior y los índices de confort térmico incluidos en la norma UNE-EN ISO 7730.

Los resultados muestran que la viga fría activa (ACB) es el sistema HVAC que garantiza mayor ahorro energético. El aire primario, que pasa a través de la ACB a alta velocidad gracias a boquillas de admisión, es descargado en el recinto una vez mezclado con el aire ambiente inducido a través de la bobina de enfriamiento de la ACB. La temperatura interior está siempre dentro de los límites de confort y su perfil de distribución espacial cerca del ideal.

Palabras clave: *sistema HVAC; viga fría activa; ahorro energético; confort térmico interior*

1. INTRODUCTION

In Europe, buildings account for 40-45% of the total **energy consumption**. CO_2 emissions from civil constructions are expected to increase continuously at a rate of 1.4% annually until 2025, faster than any other sector. This is mainly due to cooling and mechanical ventilation of the built environment, rapidly expanding markets in developed countries.

Therefore, two key targets were set by the European Council in 2007:

- A reduction of at least 20% of greenhouse gases emission by 2020;
- A 20% share of renewable energies in EU energy consumption by 2020.

Incorporating renewable energy, energy-efficient systems and sustainable design features in buildings allow the reduction of both the resource depletion and the adverse environmental impacts of pollution generated by energy production. Nearly zero-energy buildings should provide high-quality interior environments with the least primary energy consumption.

The Indoor Environment Quality (IEQ) is defined as the set of the environmental conditions existing in a closed space and influences the **indoor air quality** (**IAQ**). The optimization of the ventilation system protects users from unpleasant odours and contaminants such as volatile organic compound (VOCs) which can cause the so called “sick building syndrome”.

2. OBJECTIVES

In this paper, starting from a four-storey **glazed office building** (Figure 1), the aim is to:

1. Pre-size the most energy-efficient Heating, Ventilation and Air Conditioning (**HVAC**) **system** through calculations and manufacturer’s tools;
2. Assess the **indoor thermal comfort** that the system guarantees in a typical storey plan through a computational fluid dynamics (CFD) software.

In particular, the assessment is referred to the **HVAC-terminal-system**, which directly affect the indoor thermal comfort. A comparison between an active chilled beams (**ACB**) **system** and a common variable air volume (**VAV**) **system** serving a typical storey is carried out.

Figure 1: Rendering of the building analysed in Milan

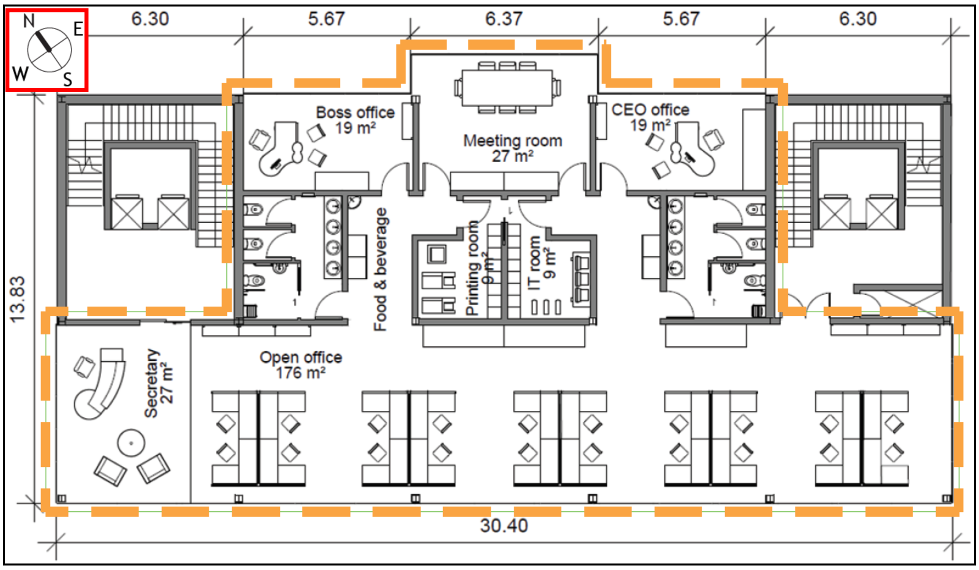
3. METHODOLOGY AND CASE STUDY

3.1. Building performance in the environment

The adoption of sustainable and energy-efficient design features is the first step to reduce the energy consumption of the built environment.

The construction analysed (Figure 1) is a glazed four-storey office building in Milan city centre, Italy. It is an L-shape complex composed by two identical blocks connected by a common lobby at the ground floor. The upper floors are exploited by companies as offices. Figure 2 shows the **typical floorplan** analysed in this paper with an open office area, two private offices, a meeting room, a printing room, an IT room and the toilets.

Figure 2: Typical floorplan with the zone modelled in the CFD software highlighted



The external envelope is made of a curtain walling system. The window's module, which is not openable and implies a need of a mechanical ventilation, is composed by a **triple glazing**, a double low-emissivity-coating, argon gaps and aluminium mullions and transoms. This expensive but performing solution guarantees an overall heat transfer coefficient (U-value) equal to 0.654 W/m^{2}K and a solar heat gain coefficient (SHGC) equal to 0.195.

A **horizontal louver** (Figure 3) stands above the glazing of each storey and allows to shade the summer solar radiation. It is made of aluminium 45° inclined lamellas and has a length of 1.00 m. Its shading-efficiency is calculated through the Italian Standard DGR 8745/2008 and through *Insight*, a plug-in of the BIM software *Autodesk Revit*. The value of the SHGC (already small due to the low-e coatings) decreases from 0.195 to 0.13.

Figure 3: External sun-shading system

The energy-behaviour of the building depends on the external environmental conditions. **Milano's climate** is humid subtropical [Cfa, according to the Köppen - Geiger climate classification system], characterized by hot and humid summers where tropical air masses dominate and quite cold winters. Air temperature varies from -10°C to 35°C and solar radiation can reach 700 W/m^2 on a vertical surface.

3.2. HVAC-system dimensioning

An HVAC-system conditions the supply air to provide an acceptable combination of humidity and temperature within the comfort zone and a sufficient amount of outside air for ventilation to prevent the indoor air from becoming stale and unhealthful. In this paper, the most-efficient **terminal subsystem** (which directly affects the users' well-being) is sized.

In a glazed office building, cooling loads are higher than heating ones since:

- Solar heat gains are the biggest loads;
- Heat gains from internal sources (people, appliances, lighting) are considerable.

Therefore, the **pre-sizing** of the HVAC-system is carried out during the **summer** period (which is the most unfavourable also because the ΔT between the supply air and the indoor air is limited for comfort's reasons) considering the following boundary conditions:

- External environmental conditions;
- Building construction technology;
- Building function (office).

In large buildings like the one analysed, the HVAC-system must meet the variable needs of different spaces. For instance, the inner core with services and computer rooms do not require heating but do require cooling and ventilation; the perimeter spaces facing the outer façades require either heating or cooling as well as ventilation. Moreover, the outer rooms gain or lose heat at a variable rate (i.e. when the sun strikes one side of a building, that side has more heat gain than the shaded sides).

Two Heating, Ventilation and Air Conditioning (HVAC) plants are commonly adopted:

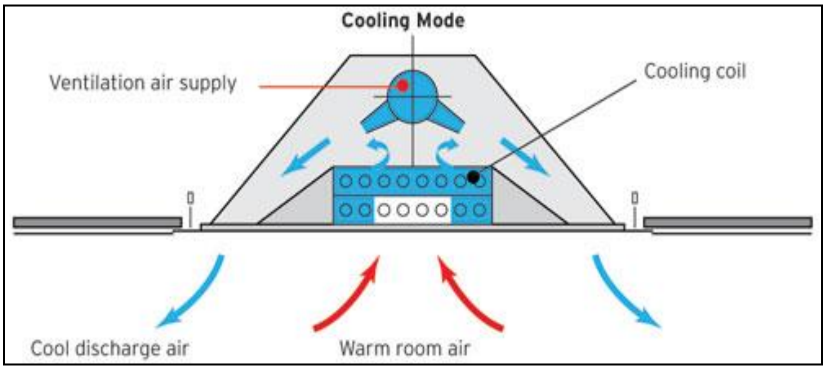
1. **All-air systems**. The air is the heat carrier fluid, guarantees air-change and controls both sensible and latent loads. It is more efficient in high occupancy-rate building (i.e. gyms, cinemas) or when the threshold of environmental conditions is strict (i.e. laboratories, hospitals);
2. **Air-water** or **mixed systems**. The air coming from outside (called primary air) is blown at the set point temperature in order to guarantee the air-change and the latent-load-control. The sensible load is controlled by another system whose heat carrier fluid is water. It is typically adopted in buildings where the sensible load is higher than the latent load and the renovation is limited (i.e. offices, houses, etc.).

The most energy-efficient solution with the first configuration is the **variable air volume** (VAV) system, which typically provides cooled air at 13°C. The **VAV terminal units**, located in the supply air duct just before the diffusers of each zone, have modulating dampers that vary the supply flowrate according to each ventilation need. They include also a post-heating coil to satisfy the varying needs of each zone. The total volume of primary air delivered by the central air handling unit (AHU) varies according to the whole demand of each zone.

In case of large cooling loads (like in glazed office buildings), a comfortable space can be provided by ventilation systems with centralized fresh air supply, in combination with **induction units** giving a fresh air discharge. Induction units do not require an additional fan because the induction principle causes a secondary air flow through the heat exchanger (Trane, 2011). **Four-pipe** terminals can circulate cold water for space cooling of some zones, while hot water for space heating of others.

Active chilled beams (ACBs) are fin-and-tube heat exchangers contained in a housing suspended from, or recessed in, the ceiling. In these induction units, primary air is provided by an external AHU while cool/hot water is circulated through a coil. The primary air enters the room via nozzles at a high velocity. This induces secondary air (room air) that cools down as it passes the coil. The mixed air is discharged into the room through slots along both sides of the beam (Figure 4). ACBs have a higher cooling capacity than passive chilled beams due to the induction process caused by the supplied air (Trane, 2011).

Figure 4: ACB functioning in cooling mode



Since an ACB typically does not contain a drainage system, the primary air system must maintain the dew point of the indoor air below the surface temperature of the chilled beam to avoid moisture from condensing on the coil and dripping into the space. Therefore, the air delivered by the external AHU should be dry enough to offset the space latent load.

The pre-sizing proves that ACBs are more efficient than VAV-systems in office buildings:

- The **indoor air quality** (**IAQ**) (related to pollution, CO_2, smoke, VOCs) is function of occupancy-rate and type of activity. In the building analysed the air-change-rate to assure a good IAQ is 12.5 $dm^3/s/p$ [5];
- The **thermal load** (**TL**) (that the HVAC-system must handle) has 2 components:
  - **Sensible load**, coming from solar heat gains, heat transfer through the envelope and internal gains (people, equipment, lighting);
  - **Latent load**, coming only from people in case of office buildings.

$$\dot{Q}_{TOT} = \dot{Q}_S + \dot{Q}_L = \dot{V}_I \times \rho_{air} \times (h_A - h_I) \quad (1)$$

Where:

- $\dot{Q}_{TOT}$, $\dot{Q}_S$ and $\dot{Q}_L$ are the total, sensible and latent load handled by the HVAC-plant;
- ρ_{air} is the density of the air;
- h_A and h_I are the enthalpies of the ambient air and of the supply (inlet) air;
- $\dot{V}_I = \dot{V}_{IAQ}$ or $\dot{V}_{TH}$ is the flowrate supplied by the HVAC-plant. It is the biggest between:
  - $\dot{V}_{IAQ}$ is the flowrate needed to guarantee the air-change and calculated through the occupancy-rate and the building's function as explained in the Standards;
  - $\dot{V}_{TH}$ is the flowrate needed to handle the thermal load obtained through a thermal balance of the building in the most critical period (in this case summer).

3.3. Indoor thermal comfort assessment

The microclimate is the set of factors (i.e. temperature, humidity, air velocity) that govern the climatic conditions of a closed environment. Most people spend 75-80% of their time inside closed buildings, thus working in a healthy environment is crucial and has positive effects on productivity. **Indoor Air Quality** (IAQ) is the environmental characteristic inside buildings that may affect human health, comfort or work performance.

Through **ventilation** it is possible to renew the stale air of an environment and replace it with cleaner air. This dilutes the concentration of harmful substances produced from internal sources (carbon monoxide, sulfuric acid and volatile organic compound or VOCs). The Reglamento de Instalaciones Térmicas en los Edificios (RITE, 2013) [5] states that the minimum **air-change-rate** depends on the use of the building. For people with a sedentary metabolic activity and a typical dressing level, it is 12.5 $dm^3/s/p$.

The parameter used in this paper to evaluate the IAQ is the **age of air**. It is a statistical value that is measured from the instant the air particle enters the room until it exits. The average age of all the air present in the room, called room mean (or average) age of air, is equal to the spatial average of the local mean ages of air.

The **thermal comfort** is defined in the Ergonomics of the thermal environment (UNE-EN ISO 7730, 2006) as "that condition of mind which expresses satisfaction with the thermal environment". The RITE (2006) [5] states that the thermal quality of the environment is satisfied if, considering a 50 % indoor relative humidity, air **temperature** in winter stays in the range $21°C < T < 23°C$ and in summer $23°C < T < 25°C$. The maximum **air velocity** is expressed in function of the temperature:

$$v \le \frac{T}{100} - 0.10 \quad [m/s] \tag{2}$$

Other parameters are the **indexes of thermal comfort** (UNE-EN ISO 7730, 2006). The Standard presents methods for the prediction of the general thermal sensation and the degree of discomfort (thermal dissatisfaction) that people exposed to moderate thermal environment feel. This thermal sensation depends on the characterises of:

- People's clothing (insulation and total coverage on the skin);
- Type of work (metabolic thermal load);
- Environment (air temperature, radiant surface temperature, humidity and air velocity).

The Predicted Mean Vote (**PMV**) index reflects the average value of the votes cast by a group of people over a 7-level heat sensation scale, where 0 stands for a person in a thermal equilibrium with the environment (i.e. the internal heat production of the body is equal to its loss to the environment). The Predicted Percentage of Dissatisfied (**PPD**), which comes from the PMV, estimates the number of people who feel unsatisfied by a too much cold or a too much hot condition.

Other two indexes express the thermal dissatisfaction caused by heating or cooling of certain parts of the body, such as the feet or the back. The Draughts Rate (**DR**) estimates the local discomfort factors due to air currents. The Percentage of Dissatisfied (**PD**) evaluates the percentage of people disturbed due to the vertical air temperature difference.

The normative UNE-EN ISO 7730 (2006) defines some **categories** according to the previous indexes. Anyhow, due to individual differences, there will always be a percentage of dissatisfied individuals. People accustomed to work and live in warm climates can accept high temperatures more easily and maintain a higher work performance than those who live in colder climates (**adaptation** principle).

3.4. Fluid mechanics

The thermal comfort achieved in a storey can be accessed through a Computational Fluid Dynamics (**CFD**) software. Since it works directly with fluids (i.e. air), a specific analysis can be carried on only through the correct definition of their characteristics and behaviour.

Fluids can be divided into compressible and incompressible. The evaluation can be done through the **Mach number**: if it is less than 0.3, the fluid is considered incompressible:

$$M = \frac{V_f}{V_s} < 0.3 \quad [-] \tag{3}$$

Where:

- V_f is the velocity of the fluid [m/s];
- V_s is the speed of sound [m/s].

With the air (incompressible since $M < 0.3$), the **hypothesis of Boussinesq** can be applied to simplify the equations and reduce the computational cost of the simulations. With this approximation, typically used in case of natural convection, the terms of mass forces can be neglected in the quantity of motion (or momentum) equations. Thus, the physical properties can be taken as constant in all the terms except in those of floating (buoyancy) forces.

The **Reynolds number** provides a measure of the ratio of inertial forces to viscous forces acting on the fluid. If Re < 2100, the flow behaves like a laminar one; if 2100 < Re < 4000, the flow is in a transition phase; if Re > 4000, the flow is turbulent. It can be determined with:

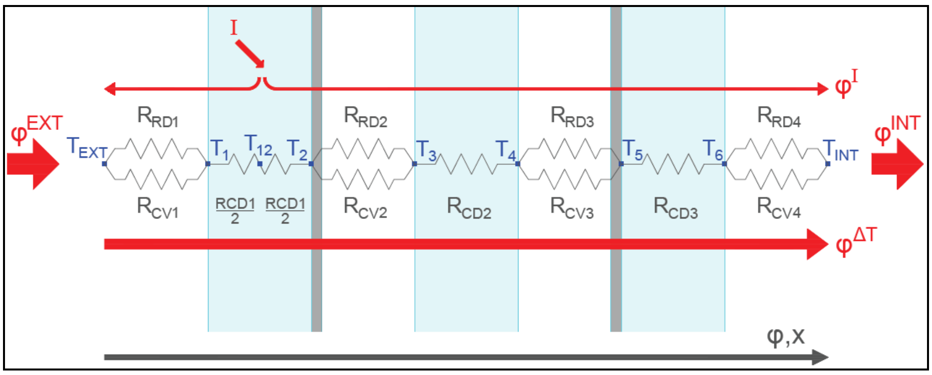
$$\mathrm{Re} = \frac{\rho \times v \times L}{\mu} > 4000 \quad [-] \tag{4}$$

Where:

- Re is the Reynolds number [-];
- L is the characteristic length [m];
- v is the velocity at the extraction grid [m/s];
- ρ is the density of the fluid [kg/m³];
- μ is the dynamic viscosity [Pa·s].

Considering a typical inlet or outlet diffuser and a typical air velocity, the Reynolds number always shows a value higher than 4000 and turbulent flow. Therefore, the friction between particles is high and they are characterized by an appreciable rotational energy.

Figure 5: Physical model adopted for the calculation of the heat flux



Since the model in the software is made of air, the temperature of the external envelope of air is considered equal to the **temperature of the interior glass pane**. This temperature is different between each façade due to the amount of direct solar radiation reaching the glazing. To calculate this value, a scheme of the triple glazing is figured out (Figure 5).

The first step is to calculate the total heat flow (sum of radiation, convection and conduction) during the most unfavourable instant (summer). It can be seen as the sum of two flows:

$$\varphi^{TOT} = \varphi^{\Delta T} + \varphi^{I} \quad \left[W/m^2\right] \tag{5}$$

Where:

- $\varphi^{\Delta T} = \frac{T_{EXT} - T_{INT}}{R_{TOT}}$ is the heat flow due to the temperature difference between the outdoor and the indoor and the total resistance of the glazing;
- $\varphi^{I} = I \times SHGC$ is the heat flow due to the solar radiation that is partially blocked through the external sun-shading and the low-emissivity coatings in the glazing, both taken into account in the factor *SHGC*.

Once the overall heat flow φ^{TOT} is known, the surface temperature of the inner glass pane can be calculated assuming stationary conditions:

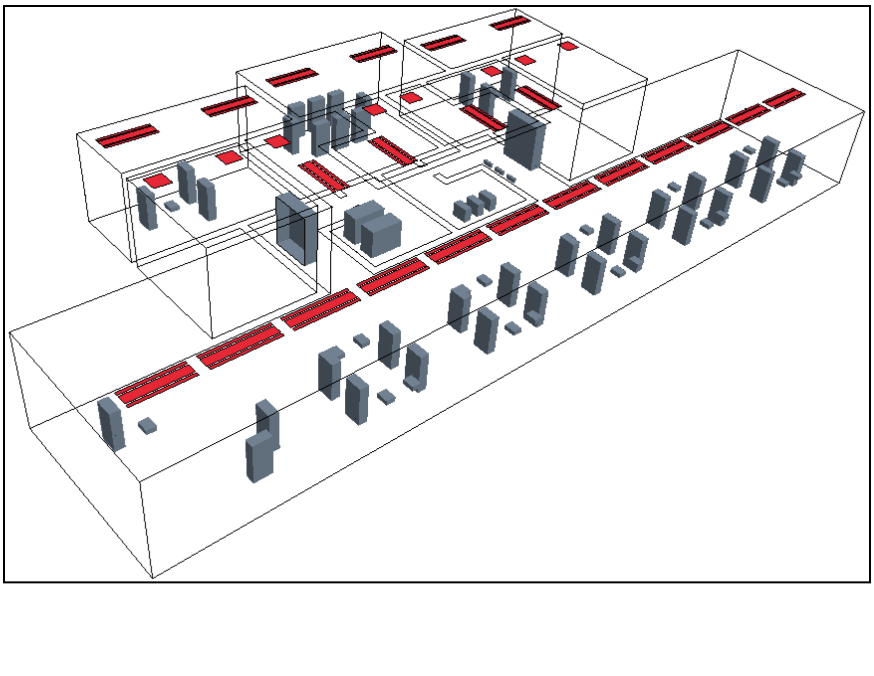
$$T_{SI} = \frac{\varphi^{TOT}}{h_{cr,\text{int}}} + T_{INT} \quad \left[°C\right] \tag{6}$$

Where:

- $h_{cr,\text{int}} = 8\, W/m^2K$ is the global internal convective-radiative factor;
- T_{INT} is considered 21°C in winter and 25°C in summer.

The last things to add in the CFD model are the internal heat sources (people computers, printers, vending machines) (Figure 6). The shapes are simplified to reduce the CFD-computational-time and the values of each power emitted are taken from the Standards [5].

Figure 6: 3D-view of the model with the internal heat sources (grey) and the ACBs (red)



4. RESULTS

4.1. Choice of the most efficient HVAC system

As anticipated in chp. 3.2, the pre-sizing done proves that an air-water system (i.e. ACBs) is more efficient than an all-air system (i.e. VAV-system) in office buildings because:

1. $SHR > 0.7$. The sensible loads are a lot higher than the latent loads as shown in the **Sensible Heat Factor** which is the ratio between the sensible loads and total loads:

$$SHR = \frac{\dot{Q}_S}{\dot{Q}_S + \dot{Q}_L} = 0.92 \quad [-] \tag{7}$$

2. $\dot{V}_{TH} >> \dot{V}_{IAQ}$. The **flowrate** needed to handle the thermal load is a lot bigger than the one needed to guarantee the air-change.

In addition to these considerations, the Italian Prestazioni energetiche degli edifice (UNI/TS 11300, 2014) and the Regional Decree (DDG 6480, 2015) show a **standardized way** to assess the efficiency of a supply system. The procedure that follows considers the fact that the points in the thermal zone have different temperatures causing losses due to **transmission** and **ventilation**.

The starting point is the **duration** [kh] of the heating season:

$$\Delta t = \frac{24 \times N}{1'000} = \frac{24 \times 180}{1'000} = 4.32\ kh \tag{8}$$

Where:

- 24 are the hours of the day;
- N = 180 is the number of days of the heating season;
- 1000 is the conversion factor between [h] and [kh].

Secondly, the **specific thermal load Φ_t** [W/m^3] of the defined thermal zone is calculated:

$$\Phi_t = \frac{Q_{need,heating}}{V \times \Delta t} = \frac{5'900\ kWh}{1'056\ m^3 \times 4.32\ kh} = 1.29\ W/m^3 \tag{9}$$

Where:

- $Q_{need,heating}$ = 5900 kWh is the yearly net sensible thermal energy need required for the heating of the thermal zone;
- V = 1056 m^3 is the volume of the thermal zone.

The UNI/TS 11300 (2014) and the DDG 6480 (2015) provides some values of conventional emission **efficiency values** according to the type of supply terminal system and the specific thermal load Φ_t.

The conventional emission **efficiency values** (**η_{eeH}**) of the terminals operating in **heating mode** are several but they don't mention active chilled beams. Anyhow, since hydronic fan-coils have a value of 0.96 and convection heaters of 0.94, active chilled beams are supposed to have **η_{eeH} = 0.95** (in case of *well-built installations*, Φ_t < 4 and zones shorter than 4 m).

The conventional emission **efficiency values** (**η_{eC}**) of the terminals operating in **cooling mode** mention active chilled beams with a value of **η_{eC} = 0.97**.

Other systems have higher efficiencies, but they don't provide fresh-air (i.e. radiant floors and ceilings). The VAV-system has an efficiency of 0.94, lower than the one of the ACBs.

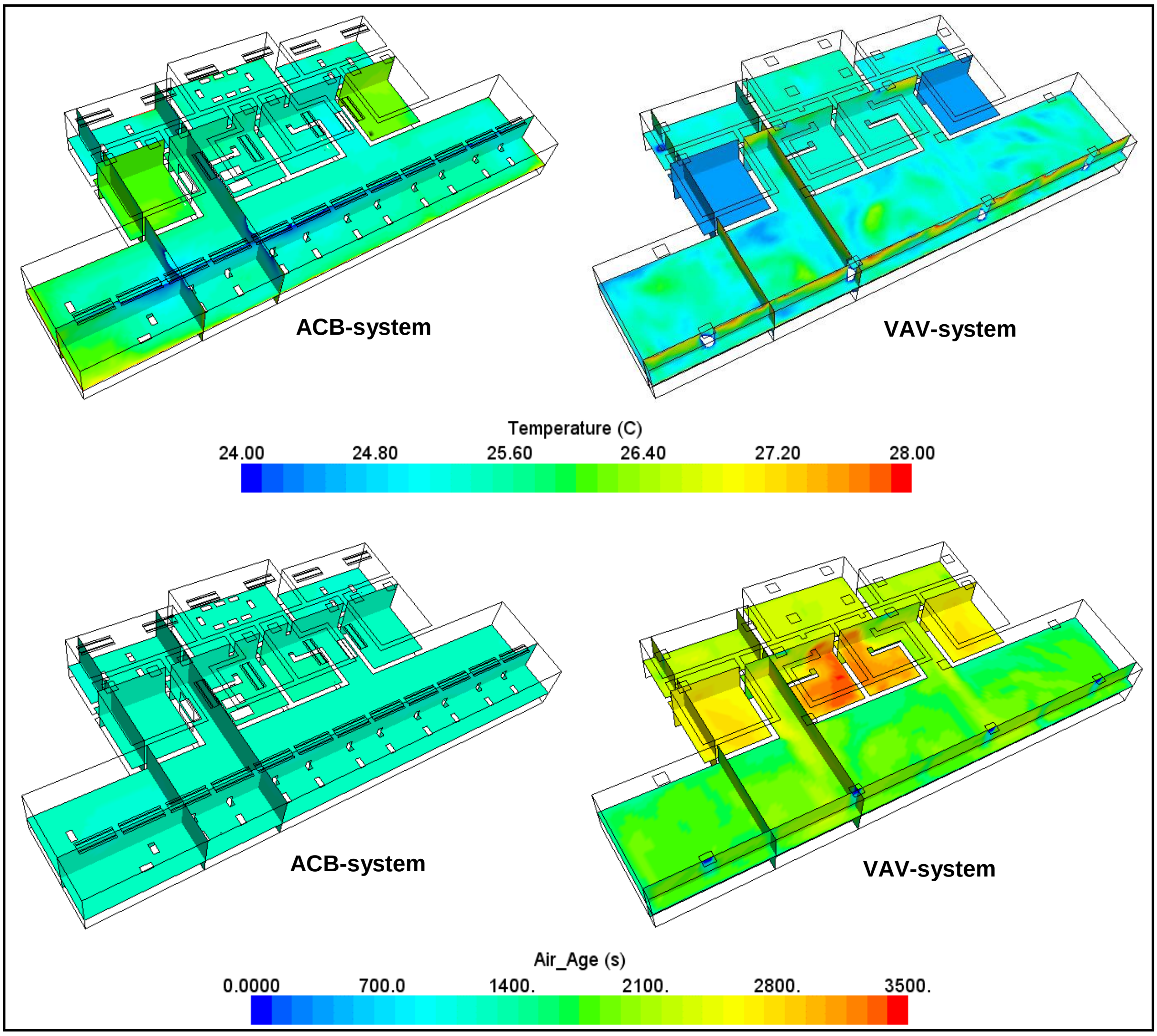
4.2. Indoor thermal comfort assessment

The first CFD-assessment is related to the thermal comfort and IAQ that an **ACB-system** and a conventional **VAV-system** guarantee in the office storey. The most unfavourable scenario for a HVAC-system serving a glazed building is considered: the hottest day with the strongest solar radiation. In the analysis, environmental conditions, terminals' position and overall inlet flowrate and temperature are kept fixed; internal heat gains are not considered.

The spatial distribution of **temperatures** inside the zone is the first feature that illustrates that an ACB-system assures a better **thermal comfort** (Figure 7 shows more homogeneous colours on the left). This is due to the fact the VAV-system, in order to guarantee the same temperature, needs to supply a higher flowrate from less air terminals causing draughts and ununiform temperatures.

The mean **age of air** shows that the ACB-system assures a better **IAQ** too. The worst value on the left is around 1200s, which corresponds to 20 minutes. On the right the IT rooms show a value close to 3600s, which means that the mean time that an air particle is stuck is an hour (Figure 7).

Figure 7: Temperature and Age of air distributions visualized with section-planes



Once the ACBs are elected the most appropriate system in the office storey, a detailed analysis is carried out during the most unfavourable summer and winter scenarios. In the analysis, environmental conditions are kept fixed while occupancy-rate varies.

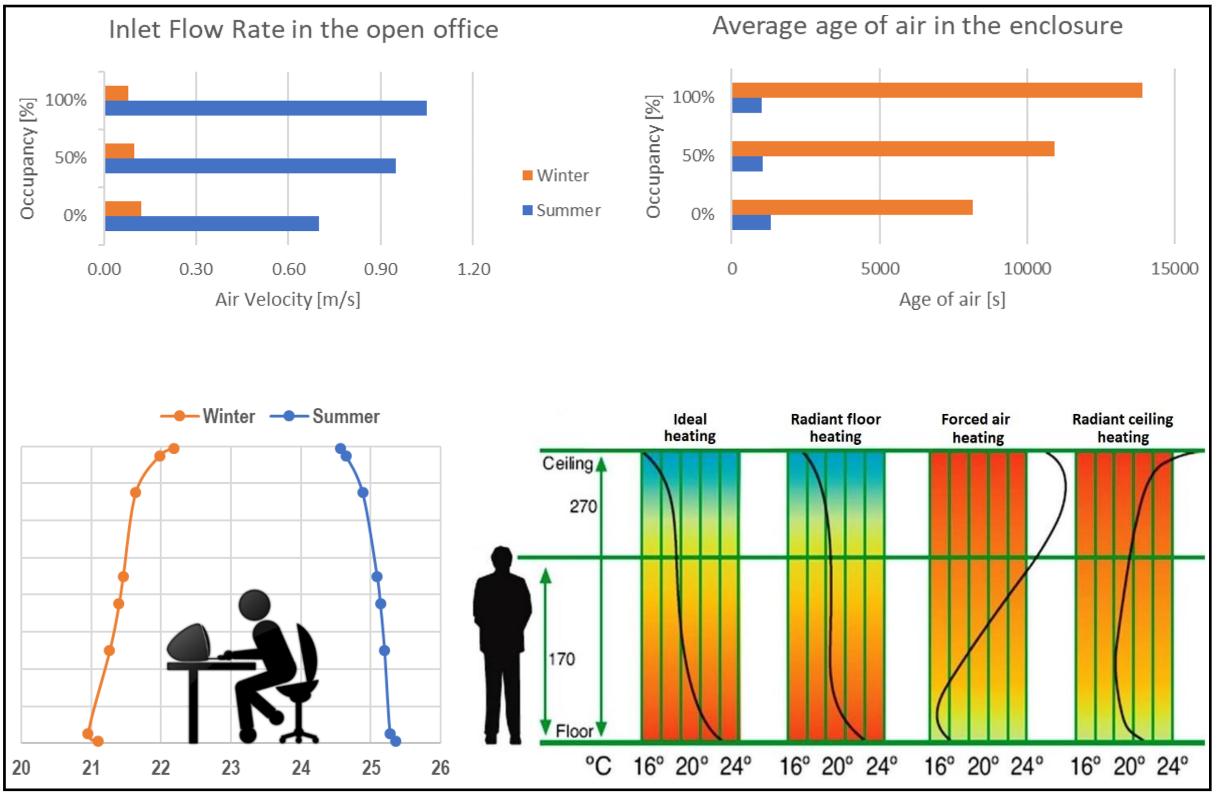
Since the supply air temperature is kept fixed, the higher thermal load caused by higher occupancy during the **summer cooling** is handled though the increase of the primary **flowrate** (which increases the induction process as well). This helps to improve the IAQ. A criterion based on the optimal temperature distribution in the workspace is used to define the exact value of the supply flowrate.

The **age of air** turns out to be strictly connected to the supply flowrate and so to the return flowrate (which is the same to guarantee the balance of mass). Higher flowrate means more air moving into the conditioned space thus a lower average age of air. The values oscillate from 22min (with 0% occupancy) to 17min (with 100% occupancy) which means that air particles remain in the thermal zone for far less than an hour, assuring a great indoor air quality level (Figure 8 in *blue*).

The distribution of **temperatures** in the space is always inside the comfort boundaries (24 °C ÷ 26 °C) and at the height of a working person is almost ideal (25°C). At 0% occupancy-rate it has the lowest value but even with 100% occupancy it remains in conditions that assure the well-being of the occupants. The stratification shows that ACBs can spread air properly, since the difference from the ceiling to the floor is less than 1°C.

The analysis shows that the **PMV** in the working area is very good (close to 0). The same can be said for the **PPD**. The situation is similar for the **DR** whose mean values, anyway, are affected by big air velocities in areas close to the beams but with no occupancy. The **PD** value shows a thermal environment of **B category** as for all the other indexes (see chp. 3.3).

Figure 8: Inlet flowrate, age of air and temperature profiles in the two seasons



ACBs are born for summer cooling, but they can handle also the **winter loads** by circulating hot water in the coils. Again, in the analysis the supply air temperature is kept fixed and a criterion based on the optimal temperature distribution in the workspace is used to define the exact value of the inlet flowrate. With 100% of occupancy there is a lot of internal heat load, thus almost no heating-need and the supply flowrate guarantees only the air-change. With lower occupancy, the flowrate is increased to enhance the induction process.

A higher flowrate guarantees a lower average **age of air**. Anyhow, the values are always quite high (from 2 to 4 hours) because the supply and return flowrates are the minimum required for renovation, due to almost no heating-need. These outcomes suggest that the minimum air-change-rate recommended by the Standards do not assure a good IAQ. As a matter of fact, Norms do not consider complex architectural layout even with a good disposition of supply and return grilles (as the good results in summer would suggest).

In all the cases analysed in winter, the average **temperature** is inside the comfort boundaries (20 °C ÷ 22 °C) and the warmest values are with 100% occupancy-rate. The spatial stratification shows that active chilled beams (as their name would suggest) are not the best system to guarantee indoor thermal comfort in heating mode (i.e. radiant floor would be better, see Figure 8). Anyhow the difference from the ceiling to the floor is only 1°C, which is still reasonable.

The mean value of **PMV** in the working area is good (close to 0). The same can be said for the **PPD**. Even though with low supply flowrate there are no strong draughts (i.e. **DR** values are very good), **PD** does not show great values because the temperature profile is not the ideal one. The comfort indexes show a thermal environment of **B category** (see chp. 3.3).

5. CONCLUSIONS

5.1. Advantages and drawback of the ACB-system serving an office storey

ACBs use significantly less energy than a conventional VAV-systems in a typical storey of an office building (see chp. 4.1). The main **benefits** are:

1. The primary air supplied is less than the one delivered in a conventional VAV-system. Therefore, ACB-systems need **smaller ductwork** allowing shorter floor-to-floor heights and a smaller AHU. This implies an energy-saving for the **supply-fan**.
2. ACBs work with **warmer water** and air. This means higher chiller COP, no need of reheat, no risk of condensation, no air filters, natural induction process working without additional fans, low sound levels. The absence of moving part or air filters makes the system virtually **maintenance free**.
3. ACBs can provide zonation through power modulation by regulating the temperature of the inlet water (which has superior **heat transfer properties** than air) or by increasing the primary supply air flowrate (respectively in case of high sensible loads and in case of high occupancy-rate)

ACBs are characterized by **drawbacks** as well:

1. The condition of **partial load**, more frequent than the one of design load, reduces the drawbacks of VAV-systems, that benefit from the unloading of the supply fan and reduced pressure loss. On the other hand, ACBs rely on high primary airflow to induce room air (Trane, 2011).
2. Due to the lack of a drainage system, **condensation** must be prevented.
3. ACBs are selected with high water flowrates to provide the required cooling capacity with a warmer water. Therefore, ACB-systems use more **pumping energy**.
4. An ACB-system has a high **installation** cost due to the low cooling capacity of a single unit and the considerable piping installed (increasing the risk of water leaks).

5.2. Indoor thermal comfort assessment

The indoor thermal comfort with an ACB-system is higher than the one with a VAV-system due to a more homogeneous temperature distribution in the space and a lower average age of air (see chp. 4.2):

1. The **age of air** is strictly connected to the **supply flowrate**. Higher flowrate means more primary air moving in the space thus a lower age of air and a better IAQ.
2. The worst values of age of air are obtained in winter in presence of the smallest flowrate, the minimum required for renovation (i.e. when there is almost no heating need). These outcomes suggest that the minimum air-change-rate recommended by the Standards must be increased to guarantee a good tenant environment.
3. High inlet air **velocities** are far away from the users and do not affect their comfort.
4. The **temperature** is always inside the comfort boundaries. Its spatial profile is close to the ideal in summer while quite bad in winter (i.e. the best temperature stratification in winter could be obtained with radiant floors).
5. The **indexes of thermal comfort** (UNE-EN ISO 7730, 2006) are always in the thermal environment of B category in regions with occupancy. Only the DR (which expresses the percentage of people estimated to be disturbed by air currents) reaches high values in extreme scenarios when high flowrates are needed to guarantee the thermal comfort.

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