E3S Web of Conferences **710**, 03001 (2026) https://doi.org/10.1051/e3sconf/202671003001
54th AiCARR International Congress

Sensible heating and cooling of indoor building spaces by eliminating local in-room humidity condensation (and the related drain pans and drainage pathways) by using calibrated humidity in air-renewal fan coil systems, for healthier NZEB, ZEB and ZCB

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Abstract. The transition towards Nearly Zero Energy Buildings (NZEB), Zero Energy Buildings (ZEB) and Zero Carbon Buildings (ZCB) requires rethinking conventional HVAC approaches to indoor thermal and hygrometric control. Traditional fan-coil or split systems often rely on latent heat removal through local condensate formation, which introduces hygiene risks due to microbial potential proliferation in condensate trays and drains. As buildings continue to be designed for lower energy use, the sensible heating and cooling opportunity presents a feasible opportunity for systems that use, at room-by-room level, sensible-only heating and cooling equipment. Examples may include: radiant cooling panels (or tubing embedded in the building structure), chilled beams and fan coils terminal units with sensible-only cooling coils. While traditional radiant panels are encountering difficulties to manage the inertia effects into a NZEB, ZEB or ZCB and chilled beams, which need to be fixed on the ceiling, sometimes are not finding sufficient space to be installed in modern buildings, the sensible heating and cooling fan coil option is becoming a very interesting possibility.

1 Introduction

Serious Indoor Environmental Quality (IEQ) issues may arise when contaminant concentrations in indoor environments reach excessive levels. Dust accumulation, stagnant water and persistently damp materials can create undesired, favorable conditions for microbial growth inside air conditioning equipment.
The most effective strategy for controlling indoor air contaminants is preferably by the elimination or (if elimination is not possible) mitigation of their sources. In the case when the primary source cannot be fully removed, the associated risks can be significantly reduced through adequate air renovation strategies, as much as possible including heat recovery systems according to EPBD IV [1].

In this context, present paper does not address in detail air renovation systems or air purification technologies, which are widely recognized as effective solutions for maintaining acceptable levels of Indoor Air Quality (IAQ) and IEQ and are extensively standardized and documented in technical literature. Instead, this study focuses on an upstream preventive approach: the elimination of potential sources of microbiological growth within HVAC systems, with particular emphasis on the removal of drain pans (from HVAC equipment at room level) and condensate drainage networks (at building level) that are considered wet areas suitable for undesired bacteria proliferation.

2 The complex problem of dust accumulation and biofilm formation in drain pans of HVAC indoor terminal units (at room level), such as fan coils and split-type room air conditioners

Indoor terminal units, including fan coil units (FCU) and split-type room air conditioners (RAC), are widely used in residential and commercial buildings. Despite advances in HVAC technology, the accumulation of dust and the subsequent formation of microbial biofilms in condensate drain pans remain a persistent operational challenge.

These phenomena, in the life cycle of a HVAC system and without proper maintenance, can degrade system performance, compromise indoor air quality (IAQ), increase energy consumption and pose potential health risks due to possible microbiological bacteria proliferation inside FCU and RAC and then diffused into the indoor ambient and potentially inhaled by humans. Indoor air contains normally suspended particulate matter originated from outdoor pollution, building materials, textiles, human activity and biological sources. As air passes through HVAC units, such as FCU and RAC, a fraction of these particles (depending on the filtration system efficiency and leakage factor) bypass filtration systems and easily deposit on wet surfaces inside the terminal units.

Experimental research [2] demonstrates that wet surfaces inside terminal units like FCU and RAC (e.g. cooling coils and drain pans) significantly enhance the deposition efficiency of powders, particulate, bacterial and fungal aerosols. Deposition fractions on wet coils can exceed 50%, compared to less than 20% on dry surfaces. Once deposited, these particles are normally transported by condensate flow into the drain pan.

Fig. 1. Illustrative non-exhaustive picture of drain pan of a fan coil unit which collecting water as condensate from the cooling coil, may become a place where also dust and particulate can be collected. The mixture of condensed water, dust and particulate can potentially create good conditions for bacteria proliferation.

Residential and light-commercial FCU and RAC typically employ low-to medium-efficiency filters, which are not designed to capture fine particles and bioaerosols. That is why for terminal units FCU and RAC, which are normally installed in-room where humans stay, this effect can assume high level of importance.
Condensate water inside FCU and RAC acts not only as a transport medium for nutrients but also as a continuous hydration source. Organic matter derived from dust, pollen, skin flakes and microbial debris can fuels rapid microbial growth. The result can lead in many cases to the formation of persistent gelatinous biofilms which progressively can contaminate also drainage pathways.
Cleaning and hygiene good practices can reduce significantly this complex problem, as we will see in following chapter 3, but as expressed in following chapter 4 it is not always so simple to be done in very compact units like FCU and RAC. In some cases, cleaning and sanitization of drain pans is almost impossible due to unit configuration, access limitations and installation constrains, that is why in present paper, we focus, not on the problem solution (how to clean the drain pan) but on the elimination of the cause (how to avoid drain pans can be the good place for bacteria proliferation), trough the investigation around "sensible heating and cooling indoor terminal units", by eliminating local in-room humidity condensation and the related drain pans and drainage pathways.

3 Existing norms and guidelines applicable to the needed cleaning and hygiene of FCU and RAC indoor units drain pans and drainage pathways

To keep HVAC systems clean, including FCU and RAC drain pans and drainage pathways, there are several norms and guidelines. Here below in a non-exhaustive way, we present some of the more significant reference texts, exploring opportunities and limits of their application in the real installation conditions.

3.1 "Procedura operativa per la valutazione e gestione dei rischi correlati all'igiene degli impianti di trattamento aria" edited in Italy with the "Accordo Conferenza Stato-Regioni 07.02.2013" [3]

This operational procedure identifies condensate drain pans of fan-coil and indoor air-treatment units as critical control points for hygienic risk management due to their continuous exposure to moisture, accumulation of organic matter, and favorable conditions for microbial proliferation.

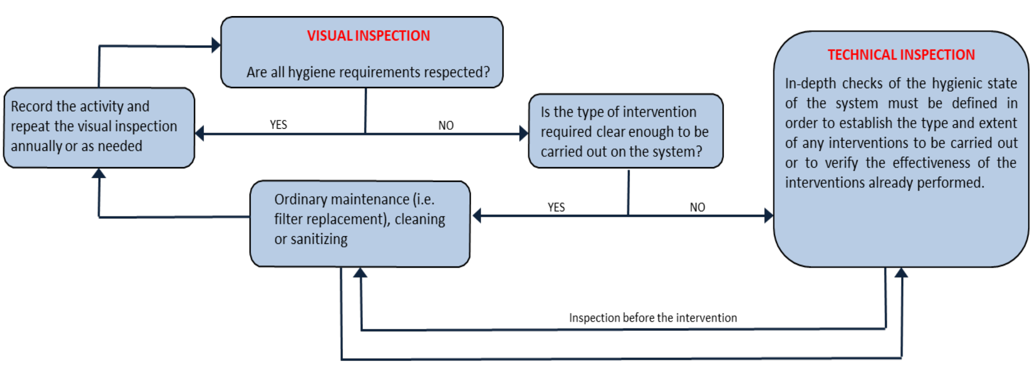

Fig. 2. Esemplificative (non-exhaustive) Flow chart of the operative procedure "Procedura operativa per la valutazione e gestione dei rischi correlati all'igiene degli impianti di trattamento aria" edited in Italy with the Accordo Conferenza Stato-Regioni 07.02.2013" [3]

The document emphasizes that stagnant water and sediment accumulation represent primary risk factors for the development of bacterial biofilms, fungal growth, and the potential spread of pathogens, including Legionella pneumophila.

The procedure requires systematic inspection, mechanical cleaning, and sanitization of drain pans as part of scheduled maintenance programs. Mechanical cleaning must aim to remove deposits, sludge, dust residues, and biofilms, while subsequent chemical disinfection using approved biocidal agents must ensure microbiological risk reduction without damaging system materials.

Fig. 3. Illustrative picture of professional activity of HVAC components inspection and cleaning from the publication "Impianti di climatizzazione: salute e sicurezza nelle attività di ispezione e bonifica" edited by Italian INAIL Institute [4]

Furthermore, the document specifies that drain pans must be designed and maintained to guarantee complete and continuous water drainage, avoiding stagnation. Verification of correct slope, unobstructed drain outlets, and adequate hydraulic flow is mandatory after every cleaning intervention. Functional testing of the drainage system is considered an essential step to prevent recontamination and operational failures.
Cleaning frequency is determined through risk assessment based on operating hours, environmental contamination levels, occupancy type, and vulnerability of occupants, with shortened maintenance intervals for healthcare facilities, hospitality environments, and high-occupancy buildings.
Overall, the procedure establishes that regular and properly documented cleaning and sanitization of FCU drain pans are essential preventive measures for safeguarding indoor air quality, minimizing biological hazards, and ensuring compliance with occupational health and public safety regulations.

3.2 "Linee guida per la prevenzione ed il controllo della legionellosi") [5] edited by the Istituto Superiore di Sanità (ISS) provides technical guidance on Legionella prevention in HVAC systems.

Also, these guidelines highlight:

- Periodic cleaning and sanitization of drain pans;
- Verification of correct drainage flow;
- Microbiological risk control documentation;
- Etc.

3.3 "EN 15780:2011 – Ventilation for Buildings, ductwork, cleanliness of Ventilation Systems" [6]

This standard defines cleanliness classification levels and inspection methodologies for HVAC systems. Although primarily focused on ductwork, its principles are directly applicable to FCU and RAC, particularly concerning heat exchangers, fans, and air distribution components, where dust accumulation and microbial growth may compromise indoor air quality (IAQ).

The standard establishes procedures for visual inspection, particle deposition limits, and periodic cleaning verification, ensuring hygienic system operation.

3.4 "EN 12097:2007 – Ventilation for Buildings – Ductwork – Requirements for Ductwork Components to Facilitate Maintenance of Ductwork Systems" [7]

This regulation specifies design and construction requirements that facilitate inspection, cleaning and maintenance. For FCU and RAC units, it provides guidance for service accessibility, enabling proper maintenance of filters, coils, fans, and condensate drain pans, which are considered critical areas for microbial proliferation and biofilm formation.

3.5 "VDI 6022 – Hygienic Standard for HVAC Systems and Units" [8]

Widely recognized as a reference hygiene guideline in Europe, VDI 6022 provides detailed prescriptions for design, installation, commissioning, operation, cleaning, and hygienic monitoring of HVAC systems. It explicitly addresses:

- Fan-coil and split-type indoor unit hygiene;
- Evaporator coil cleaning and disinfection procedures;

- Drain pan design, slope, drainage efficiency and biofilm control;
- Microbiological contamination thresholds;
- Scheduled hygiene inspections and documentation protocols;
- Etc.

This German norm is well recognized in many EU countries and it is a real reference in HVAC, particularly relevant for condensate drain pans, identifying them as critical control points for bacterial and fungal colonization, including Legionella pneumophila risk management.

4 The difficulty in real installation conditions to provide cleaning and sanitization of FCU and RAC condensate dain pans at life cycle level

Despite the availability of several solutions to keep drain pans clean and sanitized, such as the standards expressed on chapter 3 and several technical solutions, such as (non-exhaustive list): chemical treatments, UV irradiation possibilities, Photocatalytic Oxidation PCO induct solutions [9], improved filtration, antimicrobial coatings, etc. the real prevention of dirty and bacteria proliferation in drain pans remains challenging due to the following main factors:

- Continuous dust and particulate supplies from indoor (human activity indoor) and outdoor environments (external air pollution);
- Persistent moisture creation inside FCU and RAC when they work in cooling or dehumidification mode;
- Intermittent HVAC operation, typically depending by room occupation hours and comfort levels required, leads to repeated wet-dry cycles that favour microbial survival and biofilm resilience;
- Structural/dimensional constrains typical of compact FCU and RAC units, that in most cases do not permit 100% of access to the drain pan surfaces potentially exposed to dirt and biofilm (see exemplificative pictures 4a and 4b, which can well represent typical installations). Condensate trays and drainage pipes are frequently difficult to access for inspection, cleaning, and sanitation due to spatial constraints. Drain pans in indoor terminal units are quite often shallow, narrow and can be geometrically complex, leading to stagnant zones not normally accessible to maintenance. Surface roughness, weld seams, and polymer aging further enhance microbial adhesion and EPS accumulation, making mechanical cleaning ineffective. In several cases, access to drain pans in FCU and RAC systems is often limited, making routine inspection and cleaning complicated and not possible in many cases. These components therefore represent critical zones where stagnant water may persist and interact with airborne dust and particulate matter, facilitating biofilm formation and microbial proliferation. Such conditions pose potential health risks and degrade overall IEQ.
- Biofilm resistance mechanisms that protect microbial colonies from chemical and physical removal;
- Last but not least (as unfortunately it is very diffused) improper / inconsistent / non constant (in the life time) maintenance practices.

Fig. (from left to right) 4a and 4b. Image by way of example and not exhaustive of a Duct type indoor RAC unit (4a) and FCU (4b) installation where proper maintenance, cleaning and sanitization of drain pan is simply impossible or extremely complicated, without extraordinary operations of complete disassembling of the unit or modify substantially ceiling access. Even with disassembling the unit: several hidden parts of the drain pan are anyway not reachable (e.g. the part of the drain pans behind the coil in picture 4b)

These interacting factors can create a dynamic environment where biofilm re-establishment occurs rapidly, often within a few weeks after cleaning.

5 Inspiring practices from hospitals norms related to hygienic standards in HVAC in order to respond to increased sensitivity of NZEB, ZEB and ZCB buildings to indoor environmental quality (IEQ) issues

NZEB / ZEB / ZCB represent the most advanced solutions in sustainable buildings, characterized by high energy efficiency, airtight envelopes and high-performance HVAC systems. While these approaches drastically reduce energy consumption and greenhouse gas emissions, they also introduce heightened vulnerability to Indoor Environmental Quality (IEQ) problems.

Post-occupancy qualitative evaluations reveal that, in some cases, such Energy Efficient buildings can lead to higher rates of IEQ-related complaints compared to conventional buildings. These include poor air quality, thermal discomfort, humidity imbalance and microbiological contamination.

This apparent contradiction arises because energy-optimized buildings operate closer to physical and operational boundaries, reducing system tolerance to non-programmed conditions and design (even small) errors or underestimations.

In a few words, NZEB / ZEB / ZCB, beside many energetic advantages, permit less imprecisions in design and incorrect usage of the building.

5.1 Extreme Airtightness of NZEB / ZEB / ZCB

One of the core features of NZEB / ZEB / ZCB buildings is very high envelope airtightness. The parameter n_{50} represents the air change rate at a pressure difference of 50 Pascals (Pa) between the inside and outside of a building.

It is measured using a blower door test, where a calibrated fan artificially pressurizes or depressurizes the building to 50 Pa and the airflow required to maintain this pressure is recorded.

$$n_{50} = \frac{Q_{50}}{V}$$

Where:

- **n_{50}** = air changes per hour at 50 Pa *(h^{-1})*
- **Q_{50}** = airflow rate required to maintain 50 Pa *(m^3/h)*
- **V** = internal building volume *(m^3)*

n_{50} (h^{-1})	Airtightness Level (indicative)
10–15	Very leaky (old buildings)
5–10	Poor airtightness
3–5	Moderate
1–3	Good
< 0.6	Very high airtightness (Passivhaus / NZEB level)

This drastically reduces uncontrolled infiltration and exfiltration, thereby minimizing heat losses, which is very important, energetically speaking, in NZEB / ZEB / ZCB. However, airtightness also removes the natural dilution effect that traditionally mitigated indoor pollutant accumulation.

Consequently, even small pollutant generation rates from occupants, materials, furnishings and indoor activities can lead to rapid concentration increases and therefore any kind of poor ventilation and air renewal system or improper evaluation (or poor sensoring detection) of zone by zone air renewal requirements can lead to the undesired IEQ acute problems, which, surprisingly, can become a growing concern into a NZEB / ZEB / ZCB, also if compared to traditional non energy efficient buildings.

5.2 Too High Dependence of NZEB / ZEB / ZCB from Mechanical Ventilation

Due to the high airtightness of the building envelope, indoor air quality (IAQ) and, consequently, indoor environmental quality (IEQ) in NZEB / ZEB / ZCB buildings rely predominantly on controlled mechanical ventilation (CMV) systems, which in most cases are equipped with heat recovery units (HRUs). These systems are essential to ensure adequate indoor air quality while simultaneously achieving high energy efficiency.

However, this strong dependence on CMV systems may introduce a single-point vulnerability affecting IEQ. In particular, if the airflow renewal provided by CMV systems does not adequately respond, within a “room-by-room” control logic, to variations in occupancy, relative humidity, internal odors, or volatile compounds generated by occupants or indoor materials (e.g., volatile organic compounds – VOCs), inadequate IEQ levels may occur, leading to discomfort within NZEB / ZEB / ZCB buildings.

Because CMV represents the primary air renewal mechanism in highly airtight buildings, any degradation in ventilation performance directly compromises IEQ. This can result in rapid accumulation of indoor pollutants at the room level, unless advanced decentralized mechanical ventilation strategies are implemented, characterized by high sensitivity to:

CO_2 concentration variations (sudden changes in occupancy),

Relative humidity fluctuations (e.g. bathrooms, kitchens during intensive use),

Temperature oscillations (sudden variations in internal thermal loads).

Unlike conventional buildings, highly airtight constructions do not benefit from passive air dilution or infiltration buffering. Consequently, system robustness is reduced, while sensitivity to design inaccuracies, control errors, or component malfunctions becomes extremely high.

In conventional buildings, air infiltration provided a passive safety margin against indoor contaminant accumulation, albeit at the expense of energy efficiency. In contrast, in NZEB /

ZEB / ZCB buildings, this redundancy is intentionally eliminated, rendering indoor environmental quality fully dependent on the accurate performance of mechanical ventilation systems.

This strongly favors decentralized control approaches supported by high-resolution sensing of all IAQ and IEQ parameters, in line with the Smart Readiness Indicator (SRI) framework introduced by the Energy Performance of Buildings Directive [10].

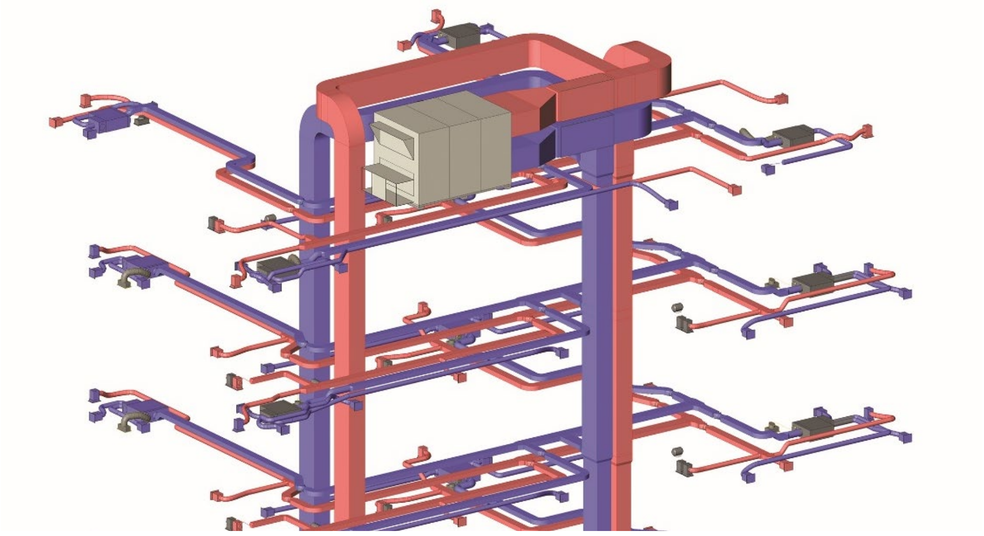

Fig. 5. Example of a dual-flow mechanical ventilation system with centralized heat recovery and aeraulic network equipped with local air distribution boxes serving the different building zones. Even when carefully designed and properly balanced, such a solution in NZEB / ZEB / ZCB buildings may experience increasing difficulty in effectively managing individual, room-by-room IEQ, that is why the elimination of potential microbiological proliferation areas like FCU and RAC drain pans, can be a very suitable strategy instead of counting mainly on ventilation to mitigate the problem.

5.3 The Italian norm UNI 11425:2011 for HVAC in hospitals

The Italian norm UNI 11425:2011 [11], which concerns CCVAC systems (Controlled Contamination Ventilation and Air Conditioning) for hospitals can be very useful to evaluate the impact of eliminating local condensate discharge points. The standard establishes very stringent requirements in HVAC for hospitals, according to which:

- all components must be designed to avoid the accumulation of contaminants;
- there must be no points where condensate can form or stagnate;
- surfaces must be easily inspectable, cleanable, and sanitizable.

From these principles derives, from a technical standpoint, the exclusion of condensate collection trays in critical areas, since they represent points of water stagnation (to varying degrees depending on whether flat or draining trays are used) and potential microbiological hotspots (including Legionella), particularly when such spaces are used intermittently and access to the condensate trays for thorough cleaning and sanitization is often difficult or impractical.

Although originally developed for the hospitals HVAC design sector, this principle should by analogy be extended to high-energy-efficiency buildings, like NZEB / ZEB / ZCB, which by their very nature feature increasingly airtight and highly insulated indoor environments. In such buildings, controlling fresh air requirements and eliminating sources of contamination become essential for safeguarding occupants health.

6 Sensible heating and cooling of indoor building spaces solutions without in-room condensate drain pan

Eliminating condensate trays and indoor condensate drainage systems and instead centralizing dehumidification in a single centralized unit (e.g. one condensate collection drain pan to be maintained, rather than one tray for each room and terminal unit), can promote improved control of indoor environmental health.

Fig. 6. Exemplificative non-exhaustive picture representing a possible solution of sensible heating and cooling of indoor building spaces by eliminating local in-room humidity condensation (and the related drain pans and drainage pathways) and by using calibrated humidity in air-renewal provided to each fan coil by a centralized air renewal and purification AHU [12]

6.1 Tube & Fin technology FCU, sensible only heating and cooling

The system architecture can be composed, at room-by-room level, by several FCU sensible only terminal units (Figure 7) equipped with a fan and a chilled-water coil mounted at the inlet from the ceiling plenum.

The humidity calibrated outdoor air (CA) received from the centralized air renewal and purification AHU unit enters each terminal unit through a flow-measuring damper (similar to, but smaller than used in a conventional VAV terminal), where it then mixes with recirculated air (RA) from the zone that has passed through the cooling coil.

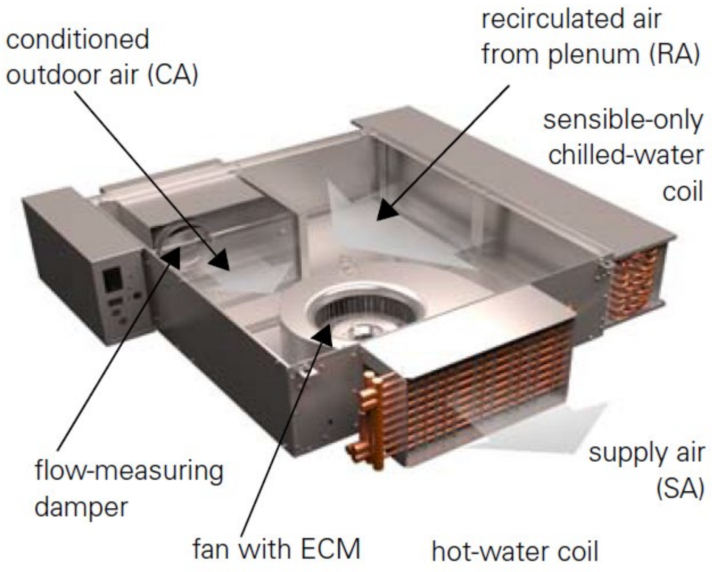

Fig. 7. Exemplificative non-exhaustive picture representing a possible sensible heating and cooling only FCU (therefore without drain pan), like a chilled beam, with calibrated humidity fresh air intake from centralized AHU, for ceiling installation using traditional tube and fin technology. [12]

Finally, the terminal fan delivers this mixed supply air (SA) to the zone through downstream ductwork and diffusers. This FCU is equipped with an electronically-commutated motor (ECM), which allows the fan speed, and therefore the supply airflow, to be varied as the zone load changes. For those zones that may require heating, a separate hot water coil may be added to the terminal unit.

The FCU is without drain pan as no local in-room water condensation is permitted, the latent heat removal is obtained providing dehumidified air in controlled quantity and humidity level.

6.2 Tube & Fin technology Chilled beam, sensible only heating and cooling

Another very widely diffused sensible only heating and cooling solution (especially in northern Europe) is represented by chilled beams using water at moderate temperatures (e.g. 18-23°C / 35-30°C) as thermal vector to provide heating function in winter season and sensible only cooling function in summer season.

As they work only in sensible cooling and heating these units do not have any drain pan in the room level. Also in this case, the latent heat removal is obtained providing dehumidified air in controlled quantity and humidity level.

This solution is a bit penalized for the large surfaces needed in the ceiling position which is mandatory for such units. So, where ceiling is limited in space or not available for HVAC systems, these units can have limitations in applicability. They are extensively used in commercial and health sector and not at all used in residential applications.

Fig. 8. Example of active type of chilled beam – Source: Roccheggiani S.p.A.: it can provide sensible heating and cooling controlling latent heat through calibrated humidity fresh air intake from centralized AHU. Normally designed for ceiling installation they use traditional tube and fin technology, without any kind of drain pan in room ambient.

6.3 Microchannel Heat Exchange Technology in Innovative patented FCU, sensible only heating and cooling

Another innovative solution is represented by a FCU using microchannel technology, which compared to the previous 2 technologies (using tube & fin coils) present the following advantages in sensible cooling performance:

Sensible Cooling Performance Exemplificative and non-exhaustive comparison based on 25mm Microchannel Coil (21 FPI) and 3 row Fin & Tube coil (16 FPI)

Metric	Fin & Tube	Microchannel	Improvement Microchannel Vs Tube & Fin
			
(A) Sensible heat from air (Temperature reduction only, no moisture removal) Sensible capacity [parametric]	1.0	1.15 – 1.40	+15/+40%
(B) Air-Side Heat Transfer Coefficient h_air [parametric]	1.0	1.3 – 1.6	+30/+60%
(C) Sensible cooling capacity per unit coil volume. Power density [parametric]	1.0	1.5–2.5	+50/+150%

Its high heat transfer efficiency, lower material mass, and full aluminium composition make it a more sustainable and resource-efficient alternative. This technology has become the preferred choice for condensers (using natural or synthetic refrigerant, dual phase fluids) and free-coolers (glycolic water, single phase fluids) in modern chillers.

In the automotive industry, microchannel aluminium heat exchangers have entirely replaced Cu–Al coils over the past two decades due to their superior performance, lighter weight, and improved environmental profile. Similar diffusion is expected in HVAC.

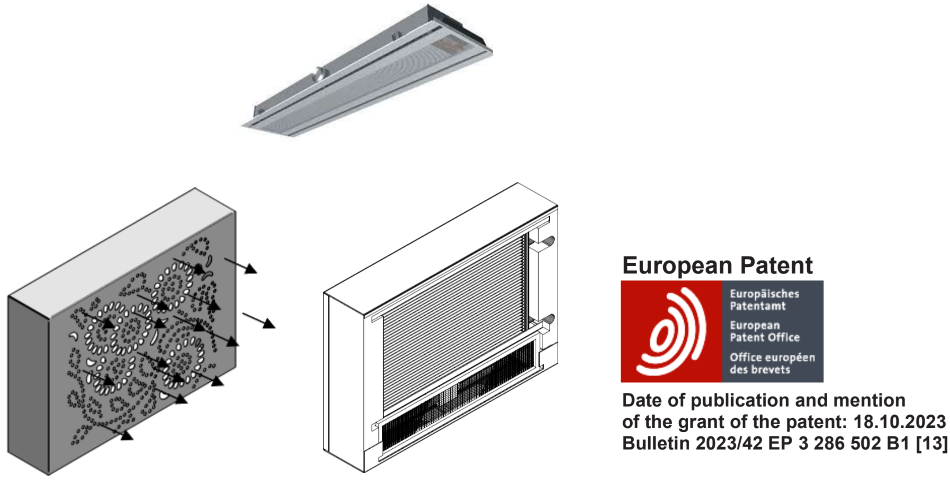

Fig. 9. Image for pure illustrative purpose, non-exhaustive, of patented solution (Patent No. EP 3 286 502 B1 obtained at European Level with specific certificate on October 23rd, 2023) [13]

This innovative Fan Coils with Microchannel Technology for sensible only heating and cooling application, is representing an innovative solution to NZEB, ZEB and ZCB, with better performances compared to traditional tube and fin technologies without drain pan as no local in-room water condensation is permitted, the latent heat removal is obtained providing dehumidified air from a centralized fresh air AHU.

7 Conclusions

Given the extensive and growing adoption of fan coil units (FCU), driven by their optimal integration with air-to-water heat pump systems, and room air conditioners (RAC), including mono-split, multi-split, mini-VRF, and VRF configurations based on air-to-air heat pump technology, these terminal units have become the dominant solutions for decentralized, room-level thermal comfort control. Their widespread application makes it essential to critically assess their hygienic and indoor environmental implications within the context of Nearly Zero Energy Buildings (NZEB), Zero Energy Buildings (ZEB), and Zero Carbon Buildings (ZCB).

In highly airtight buildings, which are a defining characteristic of NZEB, ZEB, and ZCB design, these HVAC solutions require increased hygienic attention. The substantial reduction in natural air infiltration associated with high-performance building envelopes significantly limits uncontrolled air exchange. As a result, indoor pollutants and microbial contaminants are more likely to accumulate locally, particularly when controlled mechanical ventilation (CMV) systems and air renewal strategies are not adequately dimensioned on a room-by-room basis. The persistent presence of moisture within drain pans and on heat exchanger surfaces of traditional FCU and RAC creates favorable conditions for dust deposition, microbial colonization, and biofilm development. These processes rapidly compromise indoor air quality, especially in installations where regular and effective maintenance is technically difficult or operationally unfeasible, which is quite typical for traditional FCU and RAC which design is very compact, and cleaning of the drain pan is not always easy or possible.

Within this framework, the adoption of sensible-only heating and cooling strategies emerges as a promising approach. Systems designed to exchange only sensible heat at the terminal unit level inherently avoid local condensate generation, thereby eliminating water stagnation within equipment. This design feature becomes increasingly critical as construction practices evolve toward highly sealed building envelopes, where even small moisture sources can lead to significant hygienic risks.

For these reasons, it is essential to implement systematic design strategies aimed at the complete elimination of condensate formation at the terminal unit level. Given the dominant role that FCUs and RAC systems are expected to play in NZEB, ZEB, and ZCB buildings (due to their compatibility with both air-to-water and air-to-air heat pump systems) developing and adopting condensate-free operating concepts becomes a critical priority. Such strategies offer a direct pathway to substantially reducing one of the main sources of microbiological indoor pollution, thereby enhancing long-term indoor environmental quality and occupant health in NZEB, ZEB, and ZCB.

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