

Ventilation and energy efficiency in Air Systems for future buildings: a four dimensions approach.

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Abstract Recent pandemic events are combined with a growing awareness of environmental issues, a general focus on sustainability and responsibility for future generations. All these issues converge towards a general need to improve the performance of buildings and at the same time reduce energy costs. This paper presents four different areas of improvement applicable to air systems on which it is felt that the time has come to focus conceptual and technological efforts. The four dimensions of the proposed improvement are as follows: The reduction of air leakage, the optimization of air diffusion control in VaV applications, the implementation of selective systems for the removal of specific contaminants, the system-wide contextualization of heat recovery from exhaust air. The four directions indicated are considered to offer the greatest potential for optimization in the context of air systems, and this is all the more true if these paths are taken simultaneously. They are aimed at minimizing energy effort (i.e., treated air flow rates) while maximizing performance in terms of maintaining indoor air quality. This can be done by repositioning the boundaries that until now have not allowed the full potential offered by a wise application of variable airflow systems. The approach presented is mainly a performance-based approach re-evaluated in the light of improvements in manufacturing and component characterization technologies, the possibility of considering air systems as a potentially synergistic part of more complex systems, and new sensitivities developed following the advent of pandemic events. The potential improvements in percentage terms from such an action promise to be greater than any single component implementation, but they require a change of attitude on the part of designers and a readiness on the part of manufacturers to work towards the development of standardized procedures applicable on a large scale.

1 Introduction

New constructions are characterized by energy performances that are far higher than in the past. The building features that were improved in the most recent generation of buildings are the following:

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- A better overall insulation, both from the opaque envelope assembly and from the window glazing surfaces, with an average reduction factor as per the average U-value ranging from 4 to 5, moreover a wide knowledge was disseminated toward a more conscious approach to the reduction of thermal bridges (cold bridges), i.e. with outward insulation;
- A better overall air tightness, both from the structure (walls, roofs, floors) and from the openings (when shut);
- A more accurate selection of materials for construction and furniture, with a consequent decrease in emission of indoor generated pollutants, especially when the room is not occupied.

Following a general trend of improvement of the energetic building performance, it is crucial to remind that new constructions have lost their intrinsic feature regarding the air change, due to the improved air tightness: this has the immediate consequence of reducing the energy demand for space heating/cooling, but as well implies a degradation of indoor environmental quality, and in some case has started phenomenon such as surface/interstitial condensation or mold formation in walls during wintertime. Consequently, a new requirement arose for a better control on air change and ventilation, that can be fulfilled by means of a wider dissemination of mechanical ventilation systems capable of supplying coherent fresh air rates associated with effective energy recovery on exhaust air.

More generally, the evolution of building construction has important consequences on the role played by HVAC systems: those can be considered as a complementary, beside the building and type of activity, to the achievement of reliable conditions both in terms of thermal comfort and health of the occupants.

Indeed, it is useful to remind that among the different concurring factors, the HVAC system is usually expected to be that responsible to define the indoor conditions, since it allows to control and tune in response to variation coming from other factors' evolution.

For the same activity within the building, a better performance of the building envelope has a great fallout not only on the sizing of the HVAC plant but also on the conceptual design, on the need for part load operation capability and on the widening of the possible modulation range during operations.

Air systems, with respect to other types of HVAC system, have their own specific features that make them more complex as per the interaction with the indoor environment, since their performances are not only affected by the amount of the air flowing through but also from the different strategies by which the fluid is supplied into the room, transferred within the room and among the rooms, collected by a outlet system and then exhausted and/or recirculated.

Following this path, air encounters several thermo-hygrometric processes, partly controlled and forced (within Air Handling Unit - AHU) and partly given from the interactions within the environment (in the supplied rooms); so there could be many sources of inefficiency and of undesired operational consequences.

A thorough analysis of this path, from the fresh air intake downstream to the exhaust air release, lets to identify all of the spots where a technological development and an more specific design could lead to a better performance and increased efficiencies.

In the early stage of the pandemic, AiCARR promptly published a series of documents 1 on how to configure and set up HVAC systems in order to minimize the infection risk in the indoor environment. Those documents were assumed as very valuable from professionals and institutions, helping designers, tenants and maintenance operators to manage HVAC plant in the safest possible way. Proposed actions were mainly addressed to maximize renewal flowrates, avoiding recirculation in all-air multizone systems. All these actions can be considered for existing plants as sort of emergency mode operation. Maximization of fresh air inlet, exclusion of recirculation, bypass of rotary heat exchangers (when needed) has for

sure given its positive effects on the fighting of the pandemic, however the results in terms of energy efficiency were in terms of increased specific consumption of the systems. It is then not possible to think about managing HVAC systems in the future with the same strategies that were adopted in the early stage of epidemic crisis.

It is necessary to address a coherent approach to future Air Systems for buildings. This paper presents four basic ideas as possible foundations for the design and operation of future Air systems for buildings.

2 Leakage in the air distribution system

2.1 Measuring the problem

Although there are increasing recommendations about the air tightness of air ducting, the theme is nowadays widely underestimated.

Issues related to the lack of air tightness of ductworks are mainly of two kinds:

- The first is related to the performances: the dilution capability for pollutants in the indoor environment is strictly connected to the fresh air rates and to its purity; both the quantity and the quality of air can be affected by infiltration/exfiltration in different ways. Moreover, air leakage from ducts can contribute to pressurize the ventilation shaft and the false ceiling thus causing undesired air transfer among “polluted” places and spaces that must be kept clean;
- The second is the energetic issue: in order to compensate for “lost” air in the distribution system, there is the need for fans, chillers, boilers to elaborate and treat a higher volumetric and mass flow. Indeed, infiltration of not conditioned air in returns ducts could eventually undermine the effectiveness of heat recovery action. The increase of energy consumption for chiller and boilers can be easily determined proportionally to the amount of leakage, while the increase in fan consumption is slightly more difficult to calculate since the compensation of leaked air generally requires an increase in pressure head but, in the case of exfiltration, there no simple (i.e. quadratic) law to relate pressure head and volumetric flow. This aspect is so important that in air ductwork with high leakages it occurs that the usual quadratic relation between head and volumetric flow, valid for turbulent regime, is often lost. This is a main difference between air and hydraulic networks where, conversely, the relation is valid since water piping can be considered as perfectly tight.

The sensitivity to air leakage is well acknowledged by ASHRAE, which in the volume Handbook Fundamentals of 2017 2 collects and expands the concepts that were reported in the volume Handbook Systems and Equipment 2016 3, including strong recommendations for testing the 100% of the ducting upstream and downstream VaV boxes (if present), the return ducting and exhaust ducting after the construction, and again to test at least the 25% of the ducting during the construction phase.

2.2 Characterization of leakage in Air ducting

From the point of view of determination and calculation of leakage, ASHRAE and SMACNA and other associations expressed in the past several positions, giving sample values that are not always consistent.

It was reported by the Associated Air Balance Council (AABC) 4 that a major manufacturer of ductwork maintains that a quality fabricated duct system, properly installed and sealed, can achieve [air] leakage rates lower than 1%, anyway such values cannot be easily obtained in common systems.

The recommended maximum system air leakage percentages are found in the ASHRAE Handbook 13 referring to a range between 1% and 5% of the total system design airflow at operating pressure (Leakage Class 3 is estimated to be within a range of 0.4% to 6.7% air leakage of system airflow at static pressures ranging from 125 Pa to 2500 Pa).

On the other hand, SMACNA 56 states that “1% air leakage rate for large HVAC duct systems is almost impossible to attain, and a large unsealed duct systems may develop [air] leakage well above 30% of the total system airflow.”

From the literature nowadays available it is clear that:

- Air leakage in a ductwork depends only partly from the installations and sealing phase of the ductwork. A major fraction of leakage is to be ascribed to line components so that the ASHRAE Handbook 2016 3 states: “HVAC system components, duct mounted equipment, accessories, sealants, and sealing procedures that together will meet the system airtightness design objectives”;
- A relevant role is represented by the amount of manufacturing and installation work on the ducting, then from the labor during manual construction (non-automated), and moreover from the sealing;
- Ductwork performances tend to decrease in time, due to variation in the accountability and sealing performance of the sealing materials.

Due to those reasons the characterization of air leakage of a ductwork cannot be derived from a simplistic analysis of the construction techniques and of the adopted materials, but should be verified through specific tests, for every single plant.

2.3 Standard references

The standard and references are many and different (EN, ASHRAE , SMACNA) 67891011121314 and refer to specific components (rectangular or circular ducts, made of different material, in-line components, AHU); those classify the air tightness in terms of classes, all determined by a formula as follows:

$$f = k * P_s^n * 10^{-3} \quad (1)$$

where

$f \left[\frac{m^3}{s m^2} \right]$ is the specific exfiltrated flow per square meter of leaking surface;

k is a non dimensional factor called “leakage factor”;

P_s [Pa] is the operating static pressure;

n is an exponent empirically assumed equal to 0,65 in all international standards.

Standards define classes based on k -factor ranges. The value of the exponent n of 0,65 is obtained empirically, though specific studies and experimental tests show that this value is acceptable on average, but can be specifically much different, as shown by Aydin et al. 15 who published a study proving that the value of this exponent could range between 0,32 and 0,66 according to different type of ductwork layout and sealing.

International standards propose a test applied to ductwork usually called Ducts Air Leakage Test (DALT), allowing to find the correct k factor according to specific measurements. The DALT test results to be quite expensive, quite complex and usually carried out on a sample portion of the ductwork, moreover is not always applicable to regularly operating plants since it requires a specific preparation of the network (sectioning and isolating of a portion large enough to be representative of the whole system, closing with caps and sealing of terminals), and requires specific instrumentation.

Besides the difficulties that can be encountered when try to perform a DALT test, the test itself is not intended to provide for a direct measurement of the leakage in the operating

conditions, since it is performed under steady state conditions and at pressure levels that are quite higher from the real operating ones.

Though it is possible to calculate the operating pressure level for each section of the leaking surface of the system, and then calculate for each section of the ductwork the estimated leak with the presented model, the great variation in the value of the exponent n makes the estimation of real leakage based on the application of the model inaccurate.

2.4 Research toward new test methodologies

The difficulty of quantifying the energetic and performance consequences of air leakages in operational mode and the difficulties to measure them has drawn the attention of professional designers and customers towards a prescriptive approach or to the implementation of DALT test to confirm the anticipated performance, though if a direct measurement procedure capable of estimating of leaks is not available, it is very unlikely that leaks become part of an LCC analysis.

A direct measurement of leaks, performed by calculating the difference from the air flowing through the fan and the air flowing through diffusers cannot be implemented in operating systems, since the uncertainty in each measurement of those quantities is of the same order of magnitude of the leak itself.

The idea that arises from this clearly identified problem is that there is the necessity of finding new ways for an experimental measurement of leaks, so to transform the air tightness of ductwork from an “unknown” factor into a practical parameter that must be taken into account, estimated with good accuracy and by means of simpler, and replicable, tests other than DALT.

The methodology to be identified should satisfy the following conditions:

- 1) Formulate a test procedure able to measure or directly estimate the exfiltrated airflow in operational mode;
- 2) Make use of existing instrumentation, for instance the one used in the TAB (Testing Adjusting and Balancing) activities;
- 3) To be applicable in a way that leads to determine the behavior of the whole ductwork in the same measurement session;
- 4) Lead to a more accurate value for the exponent n ;
- 5) Let the professional designer to be able to calculate, even in indirect mode, the entity of the leakage factor k , to the extent of classifying the ductworks according to the classes proposed by existing standards.

In recent years some proposals and some methodologies were made and tested to the scope. Though it is probably that a description of such hypothesis is today unripe, AiCARR constituted a working group that is now dealing with the issue, and is likely that in the near future some consistent proposal will be presented.

3 Air diffusion in VaV air systems

3.1 The framework

Variable Air Volume - VaV systems started to spread when technology and the market made available on a large scale static electric current converters, i.e. inverters.

The speed control of electric motors and subsequently of fans made possible to obtain real time control of operating conditions of fans and consequently of air flow control in an energetic efficient way.

One of the main features of HVAC system in general is the need for operating at very different load conditions, and moreover in load conditions that are much far away from the design ones. An example could be easily found due to this simple assumption: in the overall majority of HVAC systems the seasonal switch between heating and cooling mode is present; this switch takes place not only twice a year but several times, almost with continuity during mid-seasons, due to wide variation in load entity (and load sign, i.e. heating or cooling) taking place in mild weather conditions where loads are always mild with respect to the design value.

In all of Air systems with indoor temperature control, the capacity to supply thermal power can be calculated by means of a first law balance thus determining the sensible power $Q_S[kW]$ that is the product of mass flow $m[kg\ s^{-1}]$ and of the temperature difference between supply temperature of the air and ambient temperature $\Delta T[K]$

$$Q_S = m C_p \Delta T \quad (2)$$

Where $C_p[kJ\ kg^{-1}K^{-1}]$ is the specific heat of air.

Power control can be obtained by modifying either the supply temperature or the mass flow; this last option is nowadays the more convenient to implement since it can be obtained through the reduction of the fan speed, thus also reducing the electric consumption (actually also temperature reduction could mean an energy saving on the pumping side, since less water can be required through the heat exchangers).

It then follows that at reduced loads, or at almost negligible loads, it is wise to control the plant through the control of mass flow, but since Air systems also provide air renewal, the mass flow can't be lower than the minimum values given by the renewal needs.

Moreover there are two factor that limit the possibility of flow reduction in real systems, and must be considered: the first one is technological in nature, and can be ascribed to the fact that there is a minimum value for the rotation speed of electric motors below which manufacturers recommend not going for reasons related to the cooling need, while the second is the lower limit of flow acceptable by air diffusers that can't be operated at much lower values than those they are designed for.

Technological limits of the flow of fans and electric motors can be partly overcome thanks to new generations of electric motors that can achieve high efficiencies also at low speed, and in multi-zone systems the reduction of flow can also refer only to specific zones; therefore, in these systems the installation of VaV boxes can be adopted, those boxes can reduce the flow at values that are very low in a way that is not affected by the fans revolution. However, the intrinsic limits of the diffusion systems remain, and it is in this direction that a development of new solutions is needed.

For instance, in applications that are characterized by low pollution (low polluting buildings) and low occupancy, the necessary air renewal rates can be significantly lower than the design ones, and in this situation the constraints due the behavior of air diffusers can be particularly demanding to overcome.

For example, facing thermal and environmental (pollution) loads reduced at 50% of the design value, with a consequent possible reduction to 50% of flow rates, it can be hardly found that air diffusers can perform properly: this fact forces to set a minimum value of flow that keeps from taking full advantage allowable by the combination of advanced control with an innovative building concept.

A fully developed flow control system can be implemented by taking into account different needs (IAQ and load control), including a double control system that manages both the amount of fresh air and the supply temperature, reducing the temperature difference when the supply flow can't be reduced due to air change needs.

The behavior of the diffusers is generally linked to a broader concept of ventilation efficiency, which can be summarized in the ability of an air supply system to ensure that the

incoming air can reach the occupied area avoiding short circuits or areas of stagnation. There are numerous possible operational definitions of ventilation efficiency, however for all existing definitions referred to mixing systems with wall or ceiling inlets the efficiency parameter assumes a unitary value if the system allows it ensures a perfect mixing of the incoming air throughout the served space while it assumes a value less than one in the presence of bypass phenomena for which part of the supply air does not reach the occupied area. Only in the case of different and advanced systems (for example in the case of displacement ventilation or floor inlet) the ventilation efficiency can assume values higher than one.

The ventilation efficiency value guaranteed by a specific diffusion terminal depends on the geometry, the air velocities (and therefore the flow rate) and the difference between the temperature of the injected air and the ambient temperature ΔT . The recent proposals for the revision of many national standards (UNI EN 10339:1995) propose tables related to the different types of diffusers in which an efficiency parameter value referred to the maximum working ΔT in heating and cooling mode at the nominal flow rate is reported.

Since the occupied area is always in the lower part of the served rooms and since the air moves downwards when it is colder than the ambient one, in a situation of variable flow with ceiling terminals the efficiency parameter can be controlled by compensating the reduction of dynamic action of the diffuser through the modulation of the supply temperature taking care, however, to avoid localized discomfort phenomena due to cold air draft.

3.2 A possible strategy

The critical issues related to air diffusers can be met by a design of the diffusers that can work properly for a wide range of flowrates, as it is progressively implemented by the manufacturers.

A further advance is also to be identified in the combined control of temperature and mass flow.

Inside the volume Aicarr “Manuale di Ausilio alla progettazione termotecnica – Aeraulica” (AiCARR Handbook for HVAC systems – Aeraulic systems” to be published soon 16, a classification of all air diffuser types based on the maximum acceptable flow reduction was carried out, in order to evaluate possible application in VaV systems, but this can't be enough: a further step can be taken by combining the actual flow value and ΔT .

Manufacturers limit themselves to supply charts and diagrams for a correct sizing of the diffusers with reference to the maximum value of ΔT applicable to each model/type of diffuser.

The availability of diagrams suitable to evaluate diffuser performances at reduced values of ΔT could also lead to the implementation of control algorithms capable of extending the operating range of traditional diffusers, usually not designed to work at part load, and moreover of upgrading also the air diffuser conceived for VaV applications.

The consideration of these aspects implies in particular the evaluation of the vertical launch value (Drop) in both heating and cooling mode.

From a qualitative point of view, the need to avoid cold air draft in cooling mode affects the discharge velocity to the ΔT which, in turn, influences the way the air stream stays on a trajectory close to the ceiling (Coanda effect) and the way with which finally the supplied air mixes with the room air.

It is intuitive that reducing the ΔT value can prevent the risk of air draft even at a reduced flow rate.

In heating mode, the ability to let the warm air reach the occupied area depends mainly on the vertical component of the discharge speed as well as the induction effect in general. Also

in this case, the reduction of ΔT can allow the injected air to reach the lower area even at a reduced flow rate.

The described control type can therefore be based on the knowledge of the behavior of each type of diffuser and on the ways in which Throw and Drop are influenced by the combination of the flow rate and inlet temperature values.

Fig. 1, Fig. 2a,2b,2c,2d, Fig. 3 and Fig. 4a,4b,4c,4d show the behavior of a diffusion terminal operating at maximum ΔT both in heating and cooling conditions. With reference to the design situation in which Throw and Drop values are defined at the nominal flow rate, the figures show the qualitative pattern of the air stream, with reference to the envelope of the points having an air speed equal to 0,25 m/s (reference surface for the calculation of the Throw and Drop length values) and of the downward area in which the speed is reduced to half the speed (0,12 m/s), value consistent with comfort conditions.

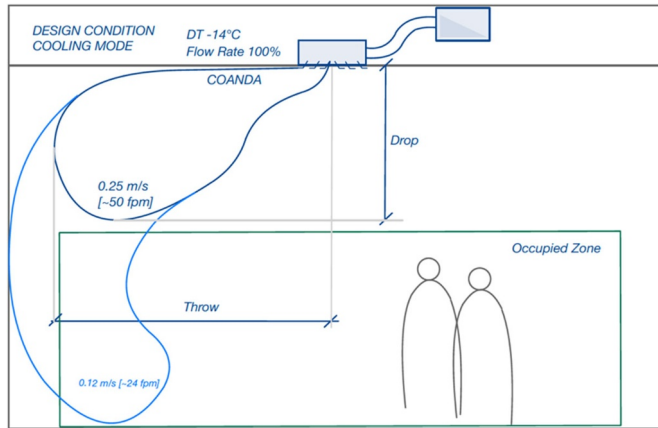


Fig. 1. Behaviour of a diffuser in cooling mode, design conditions, maximum ΔT , 100% of the rated flow

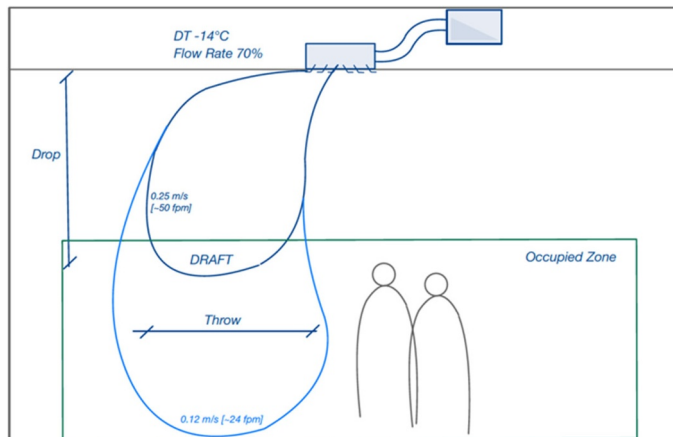


Fig. 2a. Behaviour of a diffuser in cooling mode, constant ΔT , flow at 70% of the rated value.

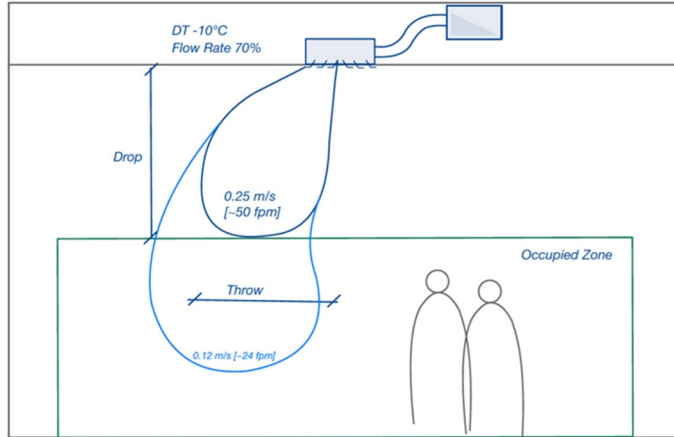


Fig. 2b. Behaviour of a diffuser in cooling mode, variable ΔT , flow at 70% of the rated value.

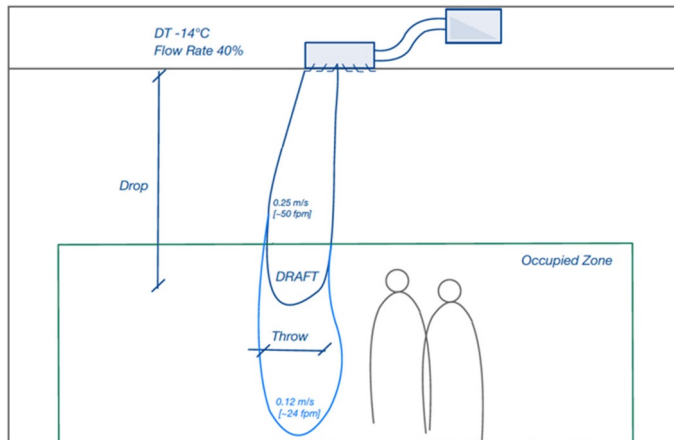


Fig. 2c. Behaviour of a diffuser in cooling mode, constant ΔT , flow at 40% of the rated value.

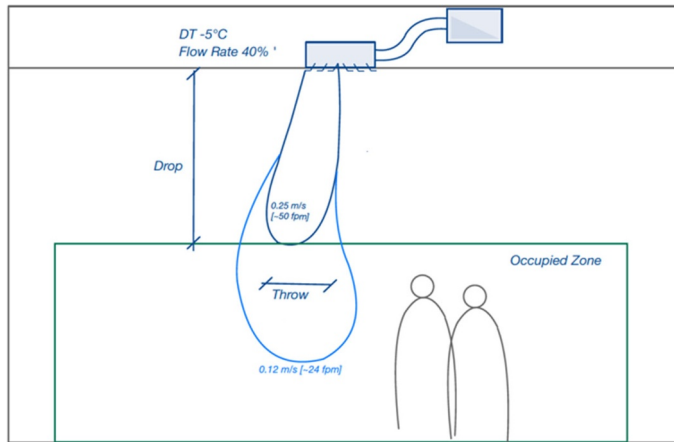


Fig. 2d. Behaviour of a diffuser in cooling mode, variable ΔT , flow at 40% of the rated value

The control of the inlet temperature allows, for example, to try keep the proper Drop value, which is correlated to the ventilation efficiency parameter. In cooling, the reduction of ΔT at partial flow rate avoids air draft, while in heating mode it can avoid the collapse of efficiency due to the buoyancy of warm air not that is not counteracted by a sufficient intake speed.

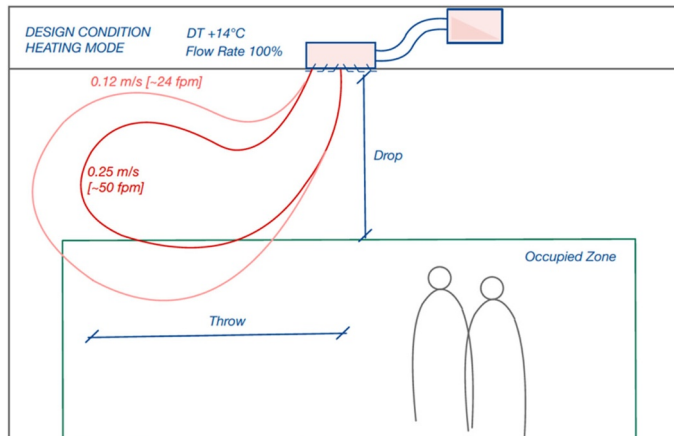


Fig. 3. Behaviour of a diffuser in heating mode, design conditions, maximum ΔT , 100% of the rated flow

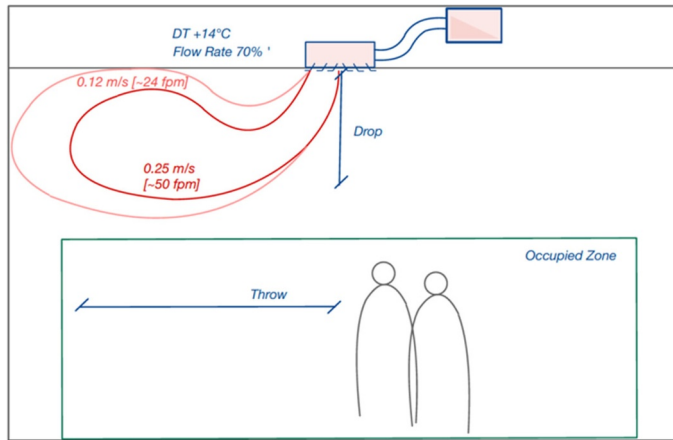


Fig. 4a. Behaviour of a diffuser in heating mode, constant ΔT , flow at 70% of the rated value.

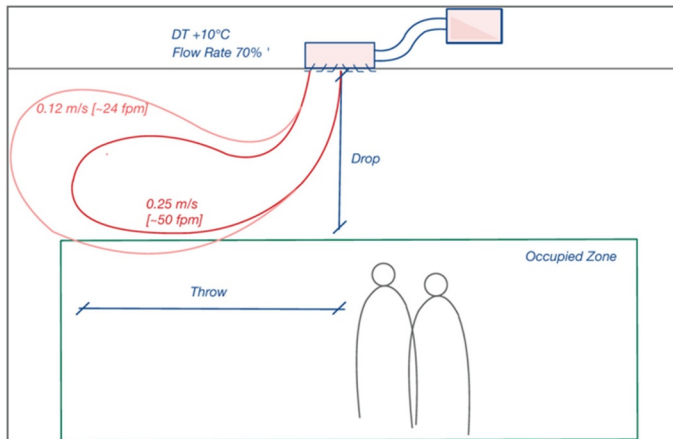


Fig. 4b. Behaviour of a diffuser in heating mode, variable ΔT , flow at 70% of the rated value.

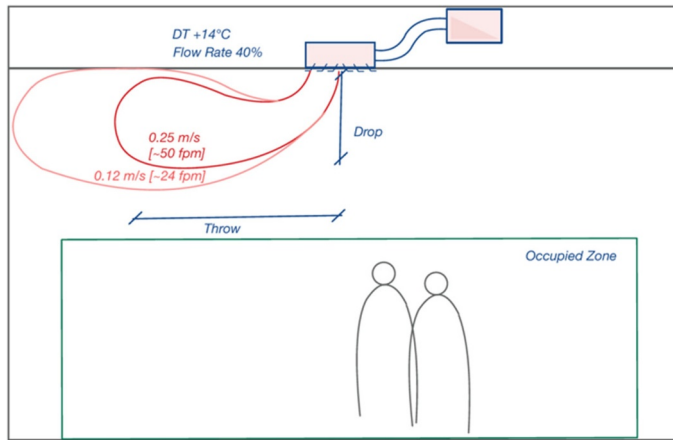


Fig. 4c. Behaviour of a diffuser in heating mode, constant ΔT , flow at 40% of the rated value.

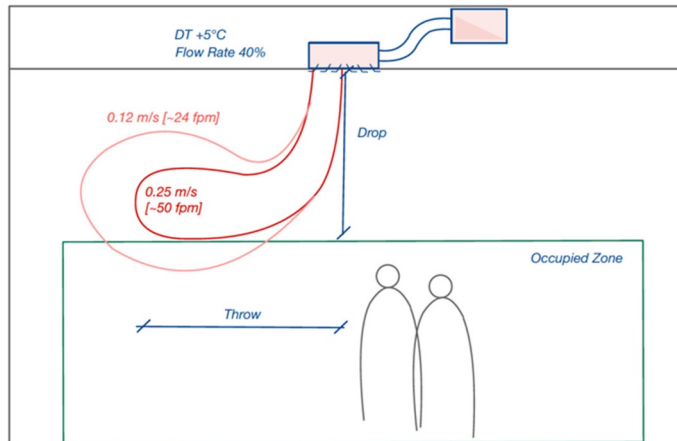


Fig. 4d. Behaviour of a diffuser in heating mode, variable ΔT , flow at 40% of the rated value.

Taking into account these aspects means especially doing the evaluation of vertical throw in heating mode and of horizontal flow in cooling mode.

As an alternative to charts and diagrams from the manufacturers, for each model of diffuser, a table could be provided showing the maximum values of ΔT that can be assumed at low speed. Such an example is given in Table 1.

For instance, in cooling mode when the need for fresh air is 50% of the design value, table shows that the maximum ΔT is $5^{\circ}C$, and as a consequence the maximum sensible power is 17,8% of the rated value.

If such a strategy could be implemented, this would lead to the proposal of a local control algorithm for airflow as well as for the inlet temperature.

Table 1. Maximum useful ΔT for different values of airflow rate, with corresponding useful sensible power.

| Mode | Flow Rate Value (100% = rated) | $\Delta T_{Max} = (T_{supply} - T_{space})$ | $Q_{S MAX} = (100\% = \text{rated})$ |
|---------|--------------------------------|---|--------------------------------------|
| Cooling | 100% (Max) | -14°C | 100% |
| Cooling | 50% (Min) | -5°C | 17,8% |
| Heating | 100% (Max) | +10°C | 37,5% |
| Heating | 50% (Min) | +2°C | 10% |

The application of this strategy would allow the implementation of a local control logic of flow rate and inlet temperature, which is well suited to be integrated, for example, in the control unit on board of VaV boxes equipped with post heating coil. The mentioned layout is shown in Fig.. These boxes can be managed by a double controller (for flow rate and delivery temperature), as well as a higher-level optimizer (integrated zone control) that implements the ventilation efficiency optimization logics. The proposed logic, referred to the values shown in Table 1, is presented in Fig, where the flow rate / ΔT compensation law is assumed to be linear as a first approximation, but further studies need to be conducted.

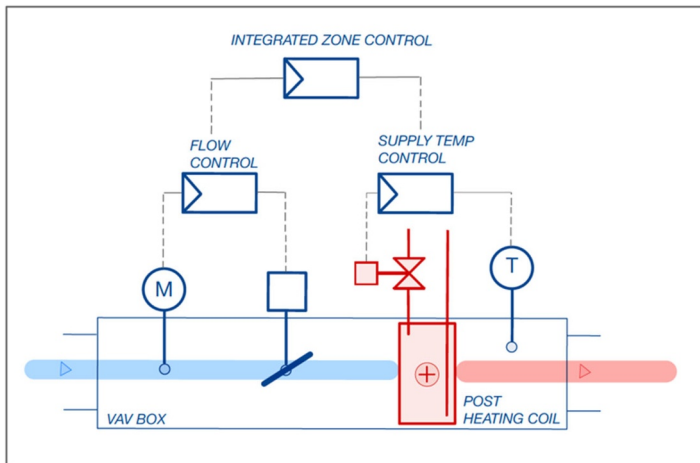


Fig. 5. Layout of a VaV box equipped with post heating coil and integrated control to optimize the ventilation efficiency.

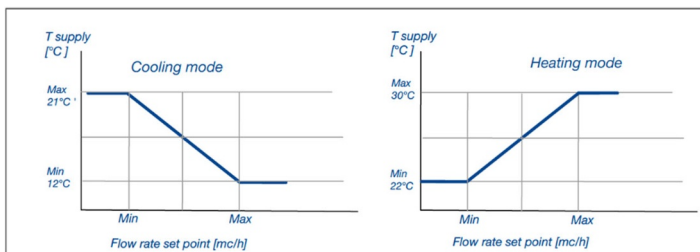


Fig. 6. Control principle with linear trend.

The inlet temperature values have been indicated in absolute value for simplicity, with reference to a set point room temperature set to 26 °C in cooling mode and set to 20 °C in heating mode.

If the flow rate is insufficient to control the heat loads and there are no water terminals, the room temperature controller will ensure that the system supplies more air, possibly by introducing or increasing the proportion of recirculated air.

4 Implementations of selective system for reduction of specific pollutants

4.1 The general framework

One of the main issues related to the optimization of air systems is directly connected to the minimization of the fresh air supply, but the need for fresh air is tied to the control of IAQ. The third dimension proposed in this paper is that of developing a standard base and a procedural base aimed to a possible implementation of techniques to reduce consciously the amount of fresh air by means of recirculated air treated by advanced pollutant reduction systems, in order to keep an acceptable IAQ level minimizing the energy consumption.

In general terms the issue of air quality can be reported to the definition of acceptability given by ASHRAE 17: “acceptable indoor air quality: air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction”.

This definition highlights two fundamental aspects, the first linked to the perception of comfort and the second linked to the hypothesis of presence of contaminants not perceived by human beings but that can still be harmful.

From the point of view of adopting strategies for the control of air quality, there is a series of actions and cautions that can be sorted by priority: the elimination of sources, the limitation of pollutants, the confinement in segregated spaces. The contribution of Air systems integrates those strategies by facilitating the containment of pollutants in selected environments (by way of relative pressure, pressure difference), implementing local extraction, and dislocating contaminants or simply mixing and diluting them with less contaminated air or uncontaminated air. The critical point is of course the availability of air with a lower concentration of a given contaminant (or of several given contaminants). The application of simple mass balance equations allows to determine the correct airflow to be supplied as a function, for each specific pollutant, of allowed indoor concentration, fresh air concentration, specific indoor emission/generation. Those calculations, performed in steady state regime and in transient, allow to define the suitable flow values to maintain concentration during time, and minimum values of air change volume [h^{-1}] to be supplied in order to remove contaminants in a given time interval called “recovery time”.

Since the contaminants are quite different from one to another and being the aim of this paper limited to the extent of applications in which air quality is intended for the well-being of the people occupying the building (thus excluding process environments), the theme of IAQ control can be reduced to identify critical contaminants or markers.

The critical contaminant is that whose concentration, in absence of control measures, reaches first the significant threshold for health defined by the cognizant authorities. For this reason, usually, the air flowrate value is specifically determined by considering the critical pollutant. For a given application, according to different scenarios, the critical pollutant can eventually change: for instance in an environment that is usually occupied by people, the contaminant to be controlled can be among those released by the human body, while in unoccupied

situation (empty room) the contaminants that require control can be those released by furniture or appliances that are left in the room. A further example is referred to the scenarios occurring when for the cleaning activities some substances/components are released while these pollutants are not usually released during the scheduled activity; In these scenarios it could eventually be required a higher ventilation rate than in normal operation and occupancy. An advanced control system should then adopt different criteria to determine part load airflows.

On the other side the marker contaminants are those that need to be accounted for when they represent an entire and wider class of contaminants that share in common the same source.

The possibility to identify a pollutant as a marker allows to adopt automatic control of airflow flow rates based on environmental probes. In the case of high occupancy applications, control systems based on detection of CO₂ or VOC concentration are widely adopted. When the marker contaminant on which the control acts is also a good indicator for the critical contaminant, the control can be assumed as effective as the diluting action is equally efficient for the whole class of considered pollutants. This generally happens when the supplied air is properly treated outdoor air, while if recirculation with selective filtration is adopted, it is necessary to check that the pollutant that needs to be removed is the one actively removed by the removal devices installed.

4.2 Remarks on air recirculation

The rising of the Sars-CoV-2 pandemic also drawn special attention on existing air systems, with a strong accent on the fact that the design conditions can be much different from the situation in which systems do operate in real situation.

The main assumption was that outdoor air can be considered as free/clean from Covid19 virus, and this pushed the professional designers, maintenance teams, tenants to modify the operational strategies of HVAC system toward the “full outdoor air” mode.

The developed models for risk assessment evaluation and to the quantification of infection risk from the working data informations available on the plants, and from the probability function referred to the possible presence of infected people within the building, now lead (more than a year after the problem arose) to conduct quantitative evaluation with respect to the management of HVAC plants and the infection risk reduction. Moreover, several ideas were born on how to re-think the design strategies, for HVAC plants that if can't be “covid-free” should be at least “covid-safe” 1819 20.

It immediately came up the need to analyze the critical aspects connected to air recirculation, however it is due to note that if on one side the use of outdoor air can easily help in the emergency phase by diluting the effect of internal sources of pollutants, on the other side it becomes very demanding in terms of energy consumption, especially in severe climatic conditions. Many HVAC plants are nowadays designed and installed with a minimum amount of recirculation, and it has been quite difficult to find specific solution to allow these systems to work in full outdoor air mode 21.

Although the market offered effective and mature technologies to remove pollutants, the absence of standard procedures to vouch a quantitative index for specific contaminant removal, associated with a specific technology or solution, prevented to adopt solutions that are also energy effective to allow the use of recirculated air.

The removal of particulate (among those i.e. particulate that is biologically infected, such as infected aerosol) is standardized for many years, and can be referred to specific standards on filtration such as ISO16890:2020 and EN 1882:2019 2223. More complex is the aspect of removal for gaseous substances, or the counteraction to specific biological agents as in the case of Covid19.

Since there is no evaluated and validated procedure consistent to the extent of technologies are different from mechanical filtration, national and international standardization bodies as AiCARR, REHVA, ASHRAE have found it difficult to consider the use of these technologies to integrate air systems with local devices for local removal or to centralized recirculation, and couldn't help but recommending to shut down recirculation or to adopt HEPA filters, that is also on the expensive side in terms of energy requirement from the fans.

The possibility to use selective removal systems should be deeply investigated as a serious alternative to the use of outdoor air, especially if those can be implemented at local level or if they can be effective enough to prevent any cross contamination associated to multizone system with air recirculation.

4.3 A proposed strategy

There is the need to consolidate methodologies and procedures for design of HVAC systems that can standardize the process of sizing local pollutant removal systems where it is determined:

- The contaminant to be removed;
- Its chemical/physical/biological features;
- The emission rate that must be considered according to its specific application/scenario;
- Thresholds and significant values that must be considered as target for design (concentration, infection risk probability);
- Removal effectiveness of the system, referred to the specific class of contaminants;
- Recirculated air flow;
- Volume of the rooms served by the plant.

The normalized procedure can be developed on the basis of the general criteria presented within the standards currently present, as an extension of the methodologies already in use to different classes of contaminants, with the possibility of integrating in a short time the consideration of classes not considered to date.

In this sense, there are working groups and supplementary proposals based on an evolution of the concepts expressed for example within the standard EN 16798-1, EN 16798-3 , CEN/TR 16798-2:2019 242526 and on criteria borrowed from WHO 26.

Finally, it is important to remember that the resolution of the criticalities referred to the IAQ connected to the use of recirculation would allow to continue to make a well-considered use of it to keep the flow rates at the diffusers without the need to increase the flow rate of external air which is not necessary for renewal purposes (point 2 of this document), to allow the use of technological solutions which foresee a minimum recirculation quota (e.g. Rooftop Units), as well as to overcome the criticalities concerning the adoption of heat recovery systems from the exhaust air which are not intrinsically free from the possibility of recirculation.

5 Systematic contextualization of the heat recovery from the exhaust air

5.1 Standardization framework

The three points presented previously have in common the goal of making it possible to minimize the flow of air processed, treated and supplied into the rooms, with particular regard to the case in which the air introduced is taken from outside.

However, beyond the possible optimizations, many air systems are mainly or totally based on the use of external air and therefore the opportunity to carry out an energy recovery using the exhaust air as a heat source is absolutely significant.

This consideration is reinforced when the system is designed for installations in latest generation buildings for two reasons:

- The first reason consists in the fact that having dramatically reduced the dispersions, the consumption for ventilation has become preponderant in percentage terms.
- The second reason consists in the fact that being able to count on buildings that guarantee excellent air tightness, there is no need to pressurize the rooms with respect to the outside to prevent infiltration: this implies that in new installations supply and exhaust air systems can be sized the same flow rate (except for exhaust of particularly dirty air). It follows that the outgoing air that can be collected and made available for recovery results to be as much as make-up air entering the building.

Over the years, the Heat Recovery Systems (HRS) applied to air systems have undergone a series of evolutions largely linked to technological development but also and above all to the development of prescriptive legislation and indirect incentives deriving from the application of simplified protocols for the energy certification of buildings.

In some situations, the search for high nominal values of recovery efficiency did not take into account the energy cost associated with the installation of devices characterized by large pressure drops. This has led in many cases to design paradoxes and award-winning solutions from the point of view of energy certification calculation procedures but hardly defensible from the point of view of minimizing the use of primary energy on an annual basis.

As per the European framework, the application of the Directive 125/2009 ERP 27 and its application effects 28 reported the issue of the choice of recovery systems completely on a prescriptive level, imposing minimum efficiencies to be respected in the face of head losses also referred to limit values.

5.2 The proposed strategies

The factors that must be taken into account in the evaluation of an exhaust air energy recovery system were formalized in an AiCARR document of 2014 29 which recalled the following concepts:

- 1) The evaluation of the efficiency of a recovery system must be carried out on an annual basis. It has to consider, in addition to the aspects related to the over consumption related to the presence of the recuperator, also that not all the recoverable energy will be used. In fact, there are frequent situations in which the recovery must be partialized, if not completely deactivated, such as in the case of operation in free-cooling mode.

For this reason the actual amount of energy to consider in order to evaluate efficiency shall be referred only to the energy that can be re-introduced into the systems, thus reducing the load on the generators.

- 2) The contextual consideration of a quantity of recovered energy (lower load on the generators) and of an energy expended for recovery (higher load of the fans) inherently calls for the consideration of a coefficient of performance (COP) that compares useful effect and cost. In this perspective, the thermal energy made available through recovery is not required from the heat generators and therefore HRS and Generator shall be compared in term of average seasonal efficiency in order to check if recovery is actually convenient. This comparison can take place by considering primary energy consumption or on the economic cost, and the two methods do not always lead to the same result: the economic comparison results to

be affected by regulatory and pricing aspects and by the incentive policies that governments put in place to favor some solutions.

- 3) The optimal solutions for HRS must always be evaluated in terms of context. In fact, in addition to what is expressed in the previous points the discussion shall be extended:
 - a. To the consideration of the climatic situation, which leads, for example, to a different assessment of the types of recovery compared on different locations;
 - b. To the consideration of the context, for example the availability of recoveries from industrial thermal waste available in the specific local that could be more convenient than the simple application of the prescriptive rules imposed by the standards. Also, the availability to connect to a high efficiency district heating may affect.

With regard to point 1) and with particular reference to the winter case, it is desirable to evaluate recovery systems capable of transferring energy not only to the incoming external air, but also capable of making it usable at central system level, for example allowing the use of the excess part to heat spaces of the building not served by the air system or domestic hot water preparation and storage.

Finally, heat recovery from exhaust air should not be intended as a simple reduction of the thermal energy required to the generators, but also as a real method of transferring power from free local thermal inputs (people, solar irradiation, processes, devices) to the whole application.

The world of air system engineering has been struggling with types of recovery as a response to the advent of the SARS-Cov2 pandemic, for which some widely applied solutions such as rotary heat exchangers have been the object of a dispute as they do not provide a physical separation between outgoing and incoming flows. This has shaken up a topic which, since the entry into effect of the European legislation, has been completely enslaved by legal requirements.

It is believed that the issue of energy recovery from exhaust air should be brought back again to the attention of designers and manufacturers and that assessment and contextualization procedures for recovery systems should be the subject of proposals by national and international associations and regulatory bodies, overcoming the mere application of the prescriptive rules which may be usefully adopted on most consolidated cases, such as residential applications or applications below defined sizes. It is anyway believed that even in these cases it would be advisable to make the appropriate distinction between applications located in very different climatic and environmental contexts.

Conclusions

The improvement of the construction quality of the buildings has made some possibilities more convenient and practicable both in terms of functional and dimensional definition of the systems with particular reference to the air systems.

The progressive reduction of thermal and pollutant loads inside buildings and the evolution of control systems has pushed the market towards variable air systems whose convenience is closely related to the ability of reducing flow rates compatibly with the trend of loads.

Recent events related to the pandemic have brought air systems back to the center of attention, forcing them in the direction of maximizing performance resulting mainly from a huge use of outdoor air.

In addition to this, the systematic review of all systems from an unprecedented point of view has brought to light the areas for improvement that have been neglected up to now.

In particular, the efficiency of the systems passes from the redefinition of the minimum flow rates based on performance criteria and on the full exploitation of new technologies and controls.

A further and important reduction of inefficiencies can be obtained from the improvement of the sealing characteristics of the networks, from the improvement of the diffusion systems and from the possibility of operating the terminals at a reduced flow rate: a proposal related to a combined control logic has been presented.

The appropriate use of contaminant removal systems may allow to reduction of external air usage where possible and the reconsideration of the energy recovery systems from the exhaust air leads to the overcoming of the prescriptive approach that characterizes the market: a series of criteria evaluation of recovery systems is proposed with the aim of creating standardized procedures for choosing the most convenient systems from time to time, systems that can be intended in terms of optimized transfer of energy from free inputs to the whole systems.

The directions indicated are functional to an overall increase in the quality level and efficiency of the systems and can also be pursued individually, however they are linked to each other and the maximum benefits can be obtained through contextual application.

References

1. AiCARR, http://www.aicarr.org/Pages/Normative/FOCUS_COVID-19_IT.aspx (2020)
2. ASHRAE, *Fundamentals Handbook*, p. cap. 34 (2017)
3. ASHRAE, *Systems and Equipment Handbook*, p. cap. 12 (2016)
4. TAB Journal. The Magazine of the Associated Air Balance Council. **Spring 2011**. Washington, D.C (2011)
5. SMACNA Sheet Metal and Air Conditioning Contractors' National Association. Vienna, Virginia. *HVAC Systems Duct Design* (2006)
6. SMACNA *Hvac Air Duct Leakage Test Manual* (2012)
7. ANSI/ASHRAE 215-2018 *Method of Test to Determine Leakage of Operating HVAC Air-Distribution Systems* (2018)
8. EN 12599, *Ventilation for buildings - Test procedures and measurement methods to hand over air conditioning and ventilation systems* (2012)
9. EN 13403, *Ventilation for buildings - Non-metallic ducts - Ductwork made from insulation ductboards* (2003)
10. EN 1751, *Ventilation for buildings - Air terminal devices - Aerodynamic testing of damper and valves* (2014)
11. EN 1507 *Ventilation for buildings - Sheet metal air ducts with rectangular section - Requirements for strength and leakage* (2007)
12. EN 15727, *Ventilation for buildings. Ducts and ductwork components, leakage classification and testing* (2010)
13. ASHRAE Standard 193-2010 (RA 2014) -- *Method of Test for Determining the Airtightness of HVAC Equipment* (2014)
14. Pat Brooks *HVAC Duct Air Leakage* — SMACNA technical resources (2019)

15. C. Aydin, B. Ozerdem - *Air leakage measurement and analysis in duct systems* Energy and Buildings **38** 207–213 (2006)
16. AiCARR, *Manuale di ausilio alla progettazione termotecnica - Aeraulica*, (2022)
17. ANSI/ASHRAE 62: 2019 *Ventilation for Acceptable Indoor Air Quality* (2019)
18. A.Cavallini, F. Busato, F. Pregliasco *Remarks on the air recirculation in HVAC systems during the SARS-CoV-2 outbreak: the case of all-air ducted plants* AiCARR Journal / Vol **63**, n. 4, 50 - 55, (2020)
19. F.Pedranzini - *Impianti HVAC e SARS-CoV-2, dobbiamo ripensare la progettazione?* AiCARR Journal Vol **66** (2021)
20. AICARR - *Protocollo per la riduzione del rischio da diffusione del SARS-CoV2-19 mediante gli impianti di climatizzazione e ventilazione esistenti* (2020)
21. F.Pedranzini, L.Cavina. A. De Piccoli, D.Rossi, - *Solutions for full-outdoor-air operation of air rooftop units with direct expansion circuit and integrated recirculation*, 52ND AiCARR International Conference, Vicenza Italy (2021)
22. ISO16890:2016 - *Air filters for general ventilation — Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM)*(2016)
23. EN 1822:2019 - *High efficiency air filters (EPA, HEPA and ULPA) - Classification, performance testing, marking* (2019)
24. EN 16798-1:2019 *Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics* (2019)
25. EN 16798-3:2017 *Energy performance of buildings - Ventilation for buildings - Part 3: For non-residential buildings - Performance requirements for ventilation and room-conditioning systems*(2017)
26. CEN/TR 16798-2:2019 *Energy performance of buildings - Ventilation for buildings - Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics – Annex I and J* (2019)
27. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (2009)
28. Commission Regulation (EU) No 1253/2014 of 7 July 2014 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for ventilation units. (2014)
29. M.Vio *Il recupero di calore dall'aria espulsa* –Guida Aicarr (2014)