Benefits of a hygienic, efficient and smart solution for ventilation systems in the era of the "New Normal"

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Abstract. Ventilation with external air is one of the most effective strategies to eliminate pathogens from indoor environments. The Air Handling Unit (AHU) is the heart of the ventilation system in commercial buildings and it is designed to achieve this goal. The guidelines for the reduction of the risk of spreading the Sars-CoV2-19 virus have introduced new operating criteria for ventilation systems, which counterbalance a better healthiness of the air in rooms with a higher energy consumption. Unfortunately, there is no standardized and shared approach to date for the designer to use as a starting point to balance these two different needs. Therefore, engineers should be aware of and pay a greater attention to the identification of practical and effective design solutions. This document proposes a technological solution for AHUs based on three key principles: Hygiene, Energy Saving and Digitization. We propose a complete and integrated architecture for the recovery of energy, humidification, system control and continuous monitoring of operating conditions, capable of ensuring health and safety, on the one hand, in compliance with the main guidelines, such as VDI 6022, and of increasing the overall efficiency of the equipment, on the other hand. The analysis compares this innovative solution with several conventional functional schemes or with systems otherwise linked to the new requirements emerged with the pandemic, and shows the resulting economic benefits, even for different climate conditions. The result shows how the selection of integrated systems for the control of ventilation, energy recovery and humidification is a winning solution that ensures healthy environments, while simultaneously reducing operating costs

1 Introduction

Buildings use mechanical ventilation for a large number of reasons, the most important of which is to maintain air quality at an optimum level to ensure occupant health and comfort [1]. Ventilation is always associated with energy consumption, which is linked with indoor conditions, outdoor climatic conditions, the type of system and how it works. The application of heat recovery systems, humidifiers and control strategies aimed at reducing

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the supply of external air according to the real demand of the surroundings, have been solutions incorporated over time in air treatment systems to optimize operation from the point of view of comfort and efficiency.

Main guidelines for reducing the risk of spreading the Sars-CoV2-19 virus (REHVA 2021 [2], ASHRAE 2020 [3], AICARR 2020 [4]), however, introduced new operating criteria to ventilation systems, that put the guarantee of safe and healthy air in closed places at the top of the list. This makes it more difficult to pursue energy saving objectives with the solutions that has been commonly adopted until then. It is therefore necessary to analyze and prepare new technological solutions for air handling units, which on the one hand allow safe and healthy operation, but on the other hand are able to ensure the overall energy efficiency of the machine and plant.

In this respect, this paper addresses a simulation comparing the estimated energy consumption for the operation of centralized air treatment plants in different configurations, comparing the benefit of an innovative solution with several conventional functional schemes.

2 Mechanical ventilation and its effects on well-being and energy consumption

The American standard ASHRAE 62-1:2010 defines ventilation as "the process of supplying and/or extracting air to and/or from a confined space for the purpose of controlling levels of pollutants, humidity or temperature". Ventilation plays a primary role in ensuring adequate air quality inside closed environments (such as offices, schools, places of entertainment, etc.).

The Air Handling Unit is the heart of the air conditioning system in commercial buildings, and is generally responsible for fulfilling this objective as well. Depending on the operating mode, primary air or all-air, it can be foreseen that a more or less significant part of the fresh air of the AHU is recirculated, while it is generally always foreseen a significant quota of fresh air taken from outside the building, with the aim of diluting the indoor environmental pollutants.

The reference standards provide indications to the designer regarding the values of the recommended ventilation flow rate according to the sources of pollution present in the building (occupants, production processes and furnishings).

In balanced mechanical ventilation systems, however, supplying fresh air means expelling a quantity of air at the comfort temperature from the conditioned environment and supplying the same quantity at an external temperature. An additional amount of energy is required to bring the supply air to the desired thermo-hygrometric conditions. This is an energy-intensive process, but it can be improved by installing a heat recovery unit between the two airflows entering and leaving the building. The heat recovery unit is an exchanger, which allows a transfer of heat and, in some cases, humidity between the exhaust airflow and the supply airflow, under the action of a difference in temperature and humidity levels. As an example, the sensible heat exchange for entering and leaving airflows is described in the psychrometric chart in Figure 1.

Commission Regulation (EU) No 1253/2014 of 7 July 2014 [9] implementing Directive 2009/125/EC of the European Parliament and of the Council, with regard to the eco-design requirements for ventilation units, states that for non-residential air handling units with a flow rate of more than 250 m³/h, a heat recovery system must always be provided. Its minimum thermal efficiency from 1 January 2018 must be 73%. In the same regulation, the presence of a thermal bypass is required and limits are established for the specific internal power of the AHU. The supply of fresh air from outside through ventilation processes can also affect the relative humidity level of the rooms. In the winter months, the replacement

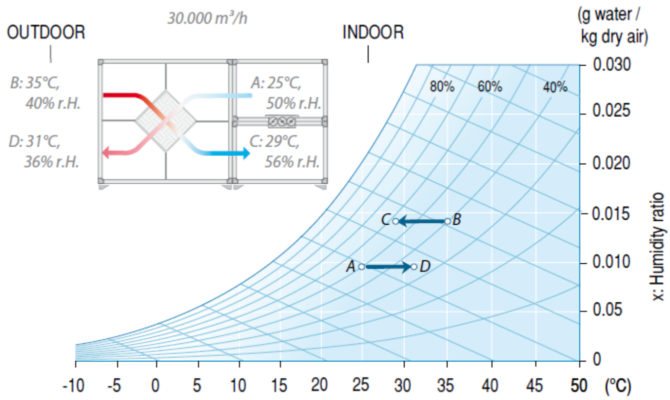
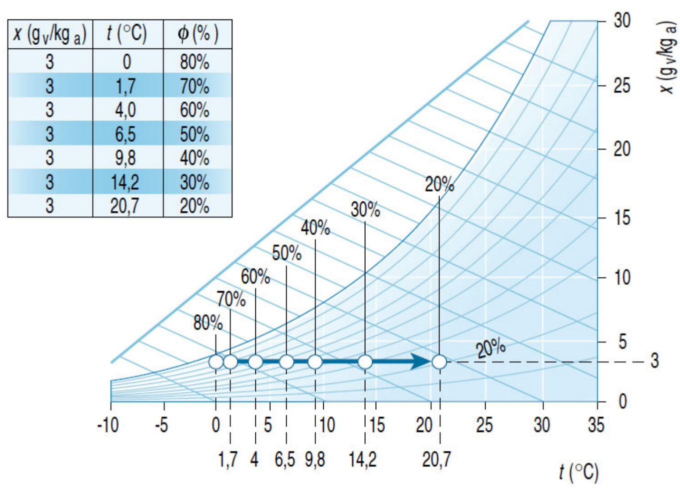


Fig. 1. Sensible heat exchange in a heat recovery system (Evaporative Cooling - AA.VV. - Carel S.p.A.[5])

of indoor air with outdoor air having a low specific humidity and the subsequent sensible heating (without any relevant contribution of internal latent loads) can lead to a reduction of the relative humidity to values lower than 20%rH, as shown in the psychrometric chart in Figure 2. These conditions can lead to situations of discomfort for the users.

The optimal range of relative humidity for the comfort of people is in fact 40% < RH < 60%, which coincides with what we want to achieve to reduce the possibility of spreading viruses (40% < RH < 60%) and overlaps with those for preventing electrostatic discharges (RH >35%) and proliferation of mould (RH < 80%). Adequate humidity control therefore, in addition to inhibiting the growth of microbes and bacteria, has the main and fundamental effect of drastically reducing their transmission potential. This is clearly explained by the Sterling diagram (Figure 3), that expresses the action of different indoor contaminants as a



x (g_v/kg_a)	t (°C)	ϕ (%)
3	0	80%
3	1,7	70%
3	4,0	60%
3	6,5	50%
3	9,8	40%
3	14,2	30%
3	20,7	20%

Fig. 2 Progressive reduction on the psychometric diagram of relative humidity due to the effect of sensible heating of winter air only (Air humidification - Technical, health and energy aspects - Lazzarin, Nalini, [6])

function of relative humidity, with identification of the optimal range for it.

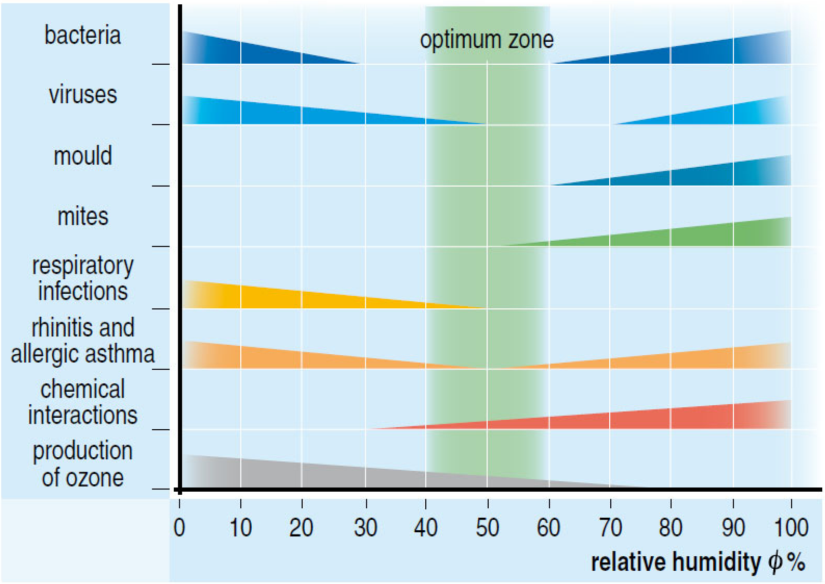


Fig. 3 Action of indoor contaminants as a function of relative humidity and identification of the optimal range for it (Sterling & co., Criteria for exposure to humidity in occupied buildings, ASHRAE Trans. 91, 1985 [6])

Integrating the humidification section into the air treatment system can bring the indoor air conditions back to an optimal situation and contribute to guarantee safe and healthy environments.

Humidification technologies are essentially divided into two: isothermal and adiabatic. In the first case (segment 1 in Figure 4), steam is introduced directly into the air stream, in which case there will be an increase in the vapour content of the air mixture, without any effect on the temperature. In the second case (segment 2 in Figure 4), water is introduced directly into the airflow, which evaporates spontaneously, obtaining a twofold effect of increasing the specific humidity, but also a simultaneous lowering of the air temperature, all with unchanged enthalpy.

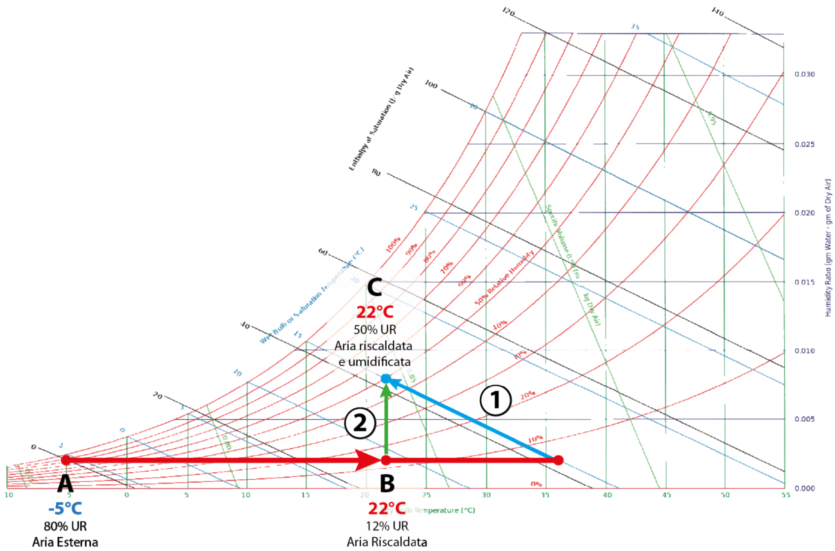


Fig. 4 Psychometric diagram with tracking of adiabatic (1) and isothermal (2) humidification processes

2.1. Aspects of hygiene for AHU's

To date, hygienic safety for AHU's typically refers to units applied in the healthcare segment, such as clean rooms and operating theatres in hospitals. Standards and certifications tend to be well established in this area, while they are less so for more general ventilation applications.

In light of the evidence and precautions that followed the SARS-CoV-2 pandemic, we believe that the application of these standards can be reconsidered and their application extended to general ventilation contexts for buildings in public use.

VDI 6022-1 "Hygiene requirements for ventilation and air conditioning systems and units"[13] is one of the normative bases for this. It constitutes the reference for the functional and constructional characteristics of the air handling unit for the hygienic and safe management, operation and maintenance of the entire ventilation system. It contains indications on the characteristics of the materials, types, sequence and arrangement of the components inside the AHU. The scope is extended from offices and meeting rooms to ventilation systems of all rooms where people may stay at least 30 days per year or at least 2 hours per day.

The minimum objective of the hygiene requirements specified in VDI 6022 Part 1 is that the quality of the air is not deteriorated by the air handling unit itself, before being released into the environment. Considering this when designing ventilation and air treatment systems is an excellent starting point for ensuring healthy environments. With reference only to heat recovery systems, humidifiers and control and automation systems, here are some specific indications.

2.1.1 Air humidification

As far as humidification is concerned, it is recommended to use drinking water and preferably demineralized water in order to prevent the minerals it contains from forming biofilms inside the AHU/channel. UV sterilization is encouraged. All parts, materials and components must not provide nutrients for microorganisms or a substrate for their growth and must be easy to clean. Corrosion-resistant components such as non-porous plastic or AISI 304 stainless steel or aluminium alloy are recommended.

The use of adiabatic humidifiers without water recirculation is implicitly recommended, as there is a lower risk of bacterial proliferation (in fact, there are no tanks for water recirculation, which are often receptacles for microorganisms, algae and bacteria). The draining pan, necessary with all adiabatic humidifiers, must be emptied continuously.

The droplet separator (mandatory), which must be designed for easy removal and cleaning, must trap airborne water droplets. It must also be made of corrosion-resistant materials.

2.1.2 Heat recovery

As far as heat recovery is concerned, the main objective is to ensure the absence of contamination between the two airflows. Where it is not possible, adopt solutions that exclude the contact between the flows (i.e. double battery recovery). Plate and rotary recovery units shall be manufactured with near zero leakage sealing specifications. In order to achieve this result, in particular for rotary recovery units, it is necessary that these are designed, installed and maintained in a workmanlike manner (as described in Figure 5), paying attention to the discharge sector and to the distribution of pressures inside the plants [11].

A second issue is related to the proliferation of bacteria on surfaces. Materials used for construction shall be smooth and corrosion resistant. If materials with a certain level of porosity are used, such as sealants, or plastic parts, they must be certified as suitable to prevent bacterial and fungal growth [12].

2.1.3 Control and regulation of the AHU

As far as the operation of the unit, and therefore its automation and control system, is concerned, it must be designed to operate the ventilation and air conditioning system in such a way as to avoid microbial growth on the surfaces of the air handling components, especially on surfaces that could remain wet. First of all, logic must be put in place to reduce the operation of the humidifiers so as to limit the humidification of the air well below saturation (VDI 6022): <90% rh; HTM 03-01: <70% rh).

In addition, abnormal operating situations must be avoided in which surfaces may be extensively and excessively dampened. For example, drying ventilation must be ensured in case of prolonged shutdown of the ventilation of the air conditioning system (for more than 48 hours), or in case of shutdown or failure of the ventilation and air conditioning system, the humidifier must automatically switch off

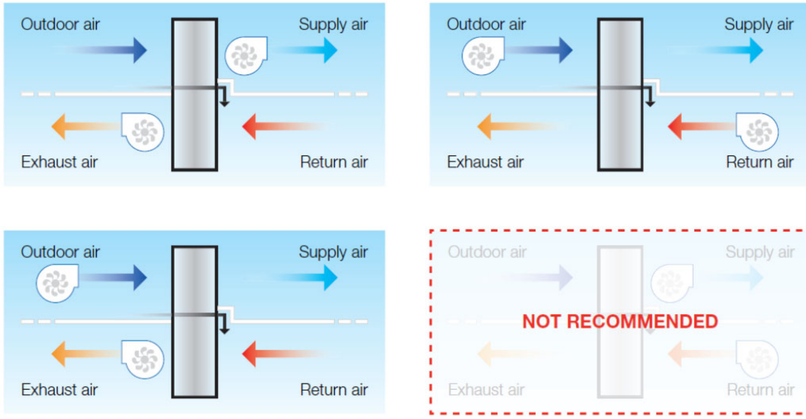


Fig. 5. Installation schemes of rotary recovery units contamination to reduce contamination between flows

3. The operating requirements of AHU's for reducing the spread of SARS CoV-2 virus

However, the outbreak of the SARS-CoV-2 pandemic introduced new guidance regarding the operation and functioning of air systems. Adequate ventilation and regular air exchange in these types of environments, in addition to maintaining comfortable conditions, have been recognized as one of the most effective strategies for reducing the risk of airborne COVID-19 infection.

The air handling units have been evaluated as a tool for the prevention of the spread of the virus inside closed premises, but on the other hand, constraints have been imposed on their operation to ensure that they do not constitute a source of risk over time.

The main regulatory and good practice references have therefore introduced new operating criteria in terms of ventilation management, heat recovery and humidity control and are summarized below.

However, all these functional implications on the machines in operation have introduced a substantial increase in energy consumption and operating costs.

In this respect, we propose a simulation comparing the estimated energy consumption for the operation of two centralized air treatment plants in two different scenarios. The first case (Figure 6) presents a centralized all-air conditioning system, with partial recirculation and constant flow rate. It represents a very common scenario in existing air conditioning systems in non-industrial buildings. The second case (Figure 7) instead presents a unit with the same features but to which new operating conditions, defined for reducing the risk of spreading the Sars-CoV2-19 virus inside the buildings, are applied.

Table 1 Comparison of strategies to reduce the risk of spreading Sars-CoV2-19 through ventilation systems

SECTION	**ASHRAE [2]**	**REHVA [3]**	**AICARR [4]**
Ventilation	As close to 100% outside air as possible. [...] ... local control of the spent air source and/or provide 100% outside, highly filtered or UV disinfected air directly to the occupancy area... can offer protection from exposure to air contaminants.	Ensure ventilation with outside air. Ventilation set to steady mode at least two hours before building occupation and reduction to night mode 2 hours after building closure. No recirculation (100% ODA).	Increased airflow rate. Forced air shutters in external air only. Continuous operation of the outside air supply.
Heat Recovery	Bypass energy recovery ventilation systems that leak potentially contaminated exhaust air into the outside supply air.	Safe use of heat recovery units. If leaks are suspected in the heat recovery sections, adjust the pressure or bypass the heat recovery section.	Rotary recovery units: algorithm to evaluate safe operation, if not, actions to intervene and correct. When it is not possible, seal the two flows. Cross-flow heat recovery units: by-pass to increase external air supply.
Humidification	40-60% RH Mousavi et al. (2019) report that the scientific literature generally reflects the most unfavourable survival for microorganisms when RH is between 40% and 60% (Level of evidence B).	25-30% relative humidity is fine if available. [...] In buildings equipped with centralized humidification, it is not necessary to modify the set point of the humidification systems (normally 25 or 30%rh).	keep relative humidity level 40-60 %rh.

"Traditional" A.H.U.

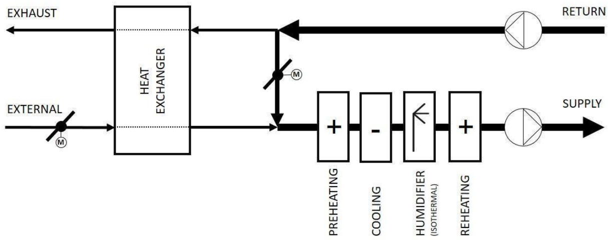


Fig. 6. Centralized A.H.U. with partial recirculation and "traditional" operating conditions

Operating conditions are assumed as follows:
-Airflow Q= 31,600 m3/h
-Heat recovery ζ= 73% sensitive, by-pass on/off
-Isothermal humidification from electrical source
-Percentage of Outside Air = 20%
-Percentage of Recirculated Air = 80%
-Constant airflow management (CAV)
-Operation 12 hours/day

A.H.U. «COVID»

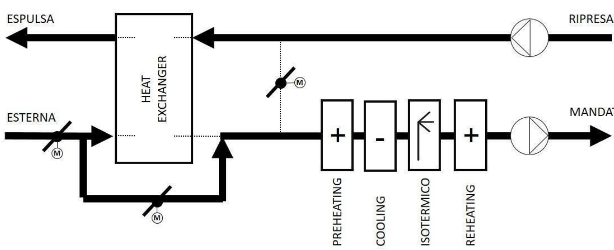


Fig. 7. Centralized AHU with operational conditions to reduce the risk of spreading Sars-CoV2-19

Operating conditions are assumes as follow
- Airflow Q= 31,600 m3/h
- By-passed heat recovery
- Isothermal humidification electric source
- Percentage of Outside Air = 100%
- Percentage of Recirculated Air = 0%
- Constant airflow management (CAV)

- Operation 24 hours/day

The simulations have been obtained with a dedicated tool simulating the operations of an Air Handling Unit able to guarantee the set point in the environment minimizing both the running cost and the total primary energy of the AHU according to the external air conditions. The simulation is based on a scenario of a small hospital with a total of 250 persons (personnel, patients, visitors), set point of 23 °C 50 rh, internal heat gains equal to 89.25 kW (sensible) and 21.25 kW (latent). In this specific case, the calculations were performed considering the bin data of the climatic conditions of the city of Milan between 6am and 6 pm, and indicated in Figure 8 with red dots overlapping the hourly climatic conditions of Milan (blue dots):

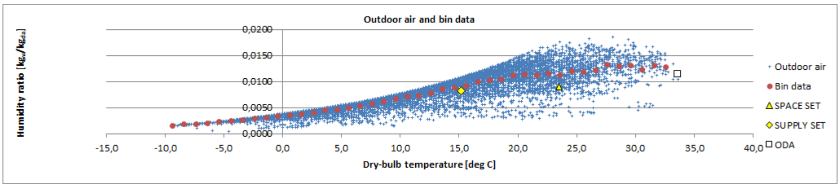


Fig. 8. Climatic conditions for Milan and bin data representation

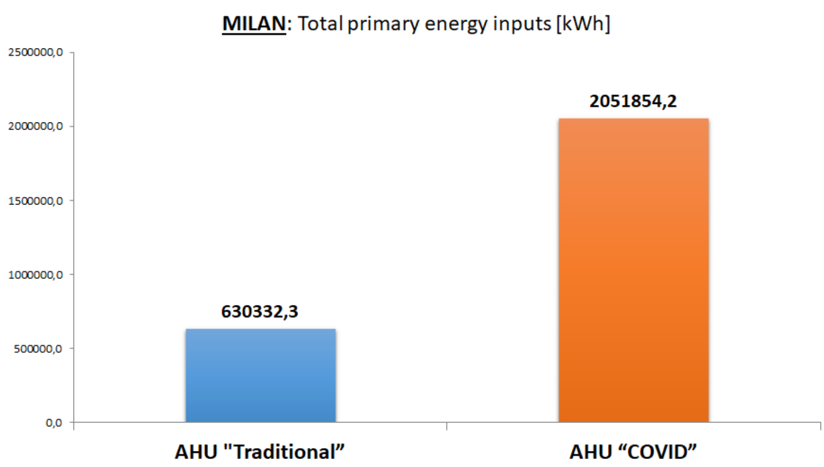


Fig. 9. Comparison of AHU consumption with "Traditional" operation and application of "COVID" protocols

The simulation results (Figure 9) show that the higher overall consumption under the operating conditions required to reduce the risk of spreading the Sars-CoV2-19 pathogen can be estimated at +1,421,522 kWh/year, or +226 %. The incidence of the different factors (Figure 10) is composed as follows:
- Higher consumption for ventilation (+290,657 kWh)
- Higher consumption for humidification (+626,787 kWh)
- Higher consumption for heating (+457,292 kWh)
- Higher consumption for cooling (+34,449 kWh)

- Higher consumption due to pressure drops at the heat exchanger (+12,338 kWh)

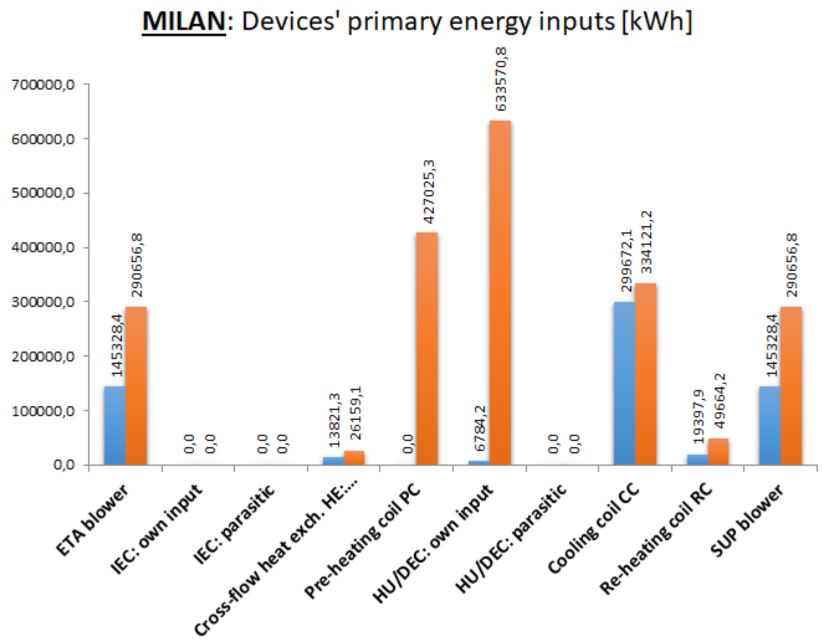


Fig. 10. Composition of the different energy consumption factors in "traditional" and "COVID" AHU

This analysis suggests that it is necessary to work on each of these contributions of increased energy expenditure with more appropriate solutions, in order to ensure a recovery of the overall efficiency of the machine, while guaranteeing adequate health and safety conditions for the environment.

4. Integrated solution for heat recovery, indirect evaporative cooling and adiabatic humidification

The following is a technological solution that is able to ensure on the one hand an increase in the energy performance of the machine, and on the other hand a containment of operating costs, all while maintaining the maximum hygienic requirements to fulfil the purposes of safety and health.

The system, schematically represented in Figure 11, consists of:

- Cross-flow heat recovery unit with hygienic and corrosion resistant characteristics. Designed and manufactured to have near zero leakage and proper maintenance. Materials as required by VDI 6022-1, inert to bacterial and fungal proliferation; Fins equipped with a hydrophilic absorbent coating (BBLUE) that allows an improvement of water distribution on the surface compared to a traditional epoxy coating when in "indirect evaporative cooling" operation [2018-Effect of plates coating on performance of an indirect evaporative cooling system]

- Adiabatic water humidifier with continuous capacity modulation for relative humidity control and evaporative cooling (Indirect Evaporative Cooling), where possible as suggested by EN13053:2020
- Direct Digital controller for Air Handling Unit with variable airflow rate, equipped with device activation strategies for the minimization of energy consumption
- Unit monitoring and supervision system capable of signaling operating conditions and assessing performance deterioration compared to design conditions

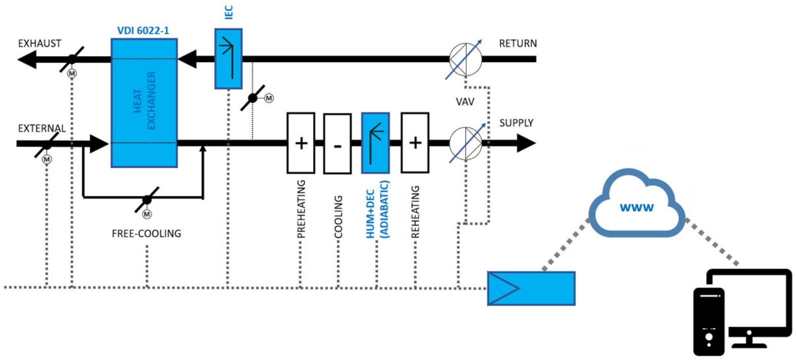


Fig. 11. Schematic configuration of an AHU equipped with a cross-flow heat recovery unit, an adiabatic humidification system and indirect evaporative cooling

With this solution, it intends to act to improve the efficiency of the factors that contribute most to increasing energy demand as a result of the requirements following the pandemic emergency.

We therefore propose a new case of analysis that considers a configuration of units according to the solutions described above and presented in Figure 12.

The new simulation proposes a comparison between the energy consumption of this application scenario and the previous ones, verifying the energy savings that can be achieved.

A.H.U. «new normal»

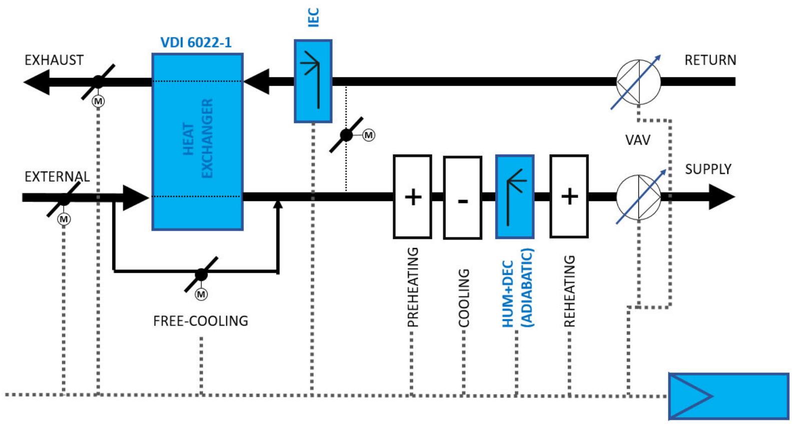


Fig. 12 Centralized AHU with a cross-flow heat recovery unit, an adiabatic humidification system and indirect evaporative cooling and operational conditions suitable to reduce the risk of spreading Sars-CoV2-19

- Airflow Q= 31,600 m3/h
- Heat recovery ζ= 73% sensitive, by-pass on/off
- Adiabatic Humidification
- Outside Air Percentage = 100%
- Indirect evaporative cooling with recovery unit dampening
- Recirculated Air percentage= 0%
- Variable airflow management
- Operation 24 hours/day

The results (Figure 13) show that the optimal modulation of all components halves the primary energy consumption of AHU "New normal" compared to AHU “COVID”, reducing it to 996,079 kWh (-52%). Instead, the consumption is greater than that of AHU "Traditional" essentially because AHU "New normal" works 24/24 while AHU "Traditional" is in place 12/24. Furthermore, even if these are minor contributions, the heat exchanger is not always bypassed, with the consequence that the pressure drop of the channels causes a higher consumption to the fans, and the IEC has its own consumption.

In detail, the changes in “new normal” AHU compared to the “COVID” AHU can be summarized as follows (Figure 14):

- Lower consumption for ventilation (-149,960 kWh)
- Lower consumption for humidification (-609,262 kWh)
- Lower consumption for heating (-411,554 kWh)
- Lower consumption for cooling (-3,791 kWh)
- Higher consumption due to pressure drops at the heat exchanger (+100,387 kWh)
- Higher consumption due to the presence of IEC (+18,405 kWh)

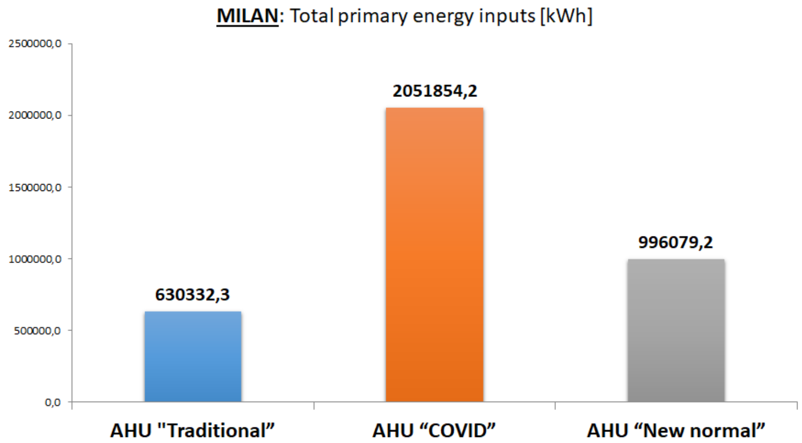


Fig. 13. Simulation of primary energy needs in the three AHU configurations for the climatic conditions of the city of Milan

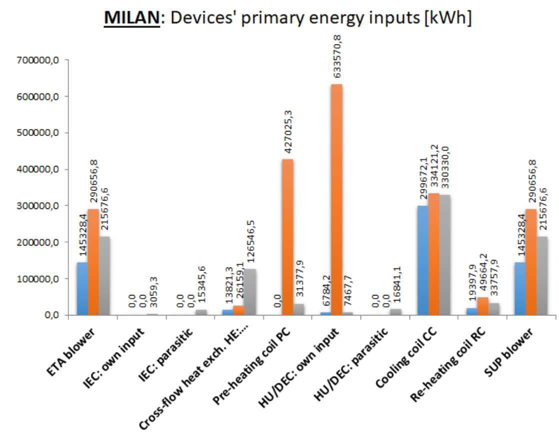


Fig. 14. Composition of the different energy consumption factors in the three AHU configurations for the city of Milan

The same simulation is then proposed also with reference to the climatic situations of Athens (Figure 15), Berlin (Figure 16) and Madrid (Figure 17), because they are different from those of Milan, in order to verify how some of these aspects can be equally significant due to different climatic conditions:

- Athens: -36% primary energy for the “new normal” AHU (1,039,924.2 kWh) compared with the "COVID" AHU (1,628,811.5 kWh)
- Berlin: -68 % (720,661.3 kWh compared to 2,256,080.9 kWh)
- Madrid: -56 % (788,378.1 kWh compared to 1,779,517.0 kWh)

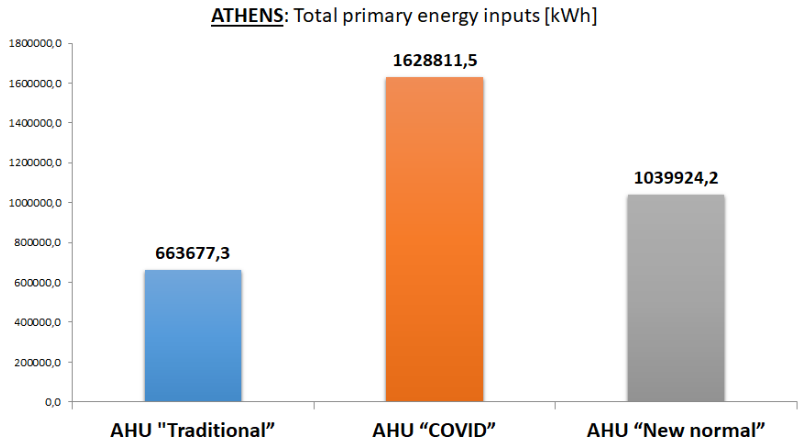


Fig. 15. Simulation of primary energy requirements in the three AHU configurations for the climatic conditions of the city of Athens

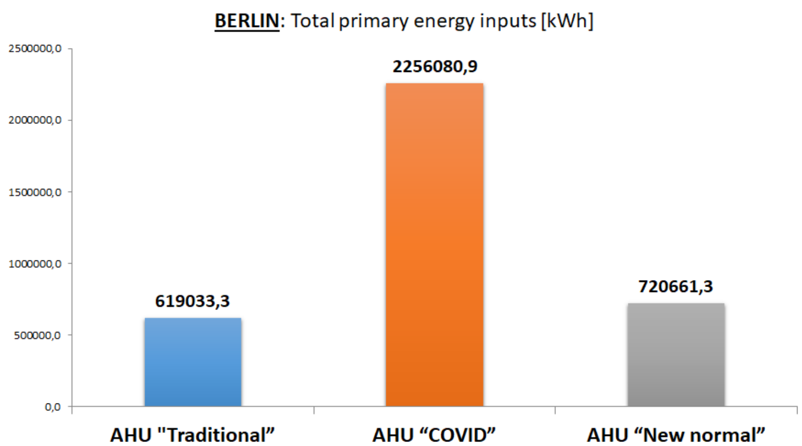


Fig. 16. Simulation of primary energy requirements in the three AHU configurations for the climatic conditions of the city of Berlin

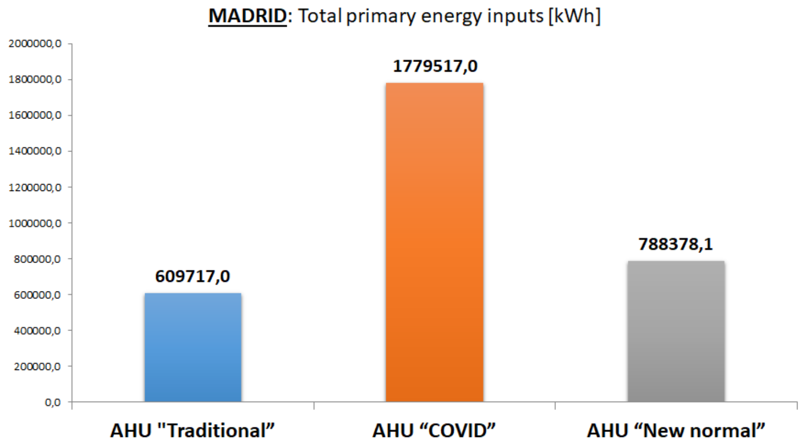


Fig. 17. Simulation of primary energy requirements in the three AHU configurations for the climatic conditions of the city of Madrid

4.1. The role of "smart" technologies for AHU's

The Internet of Things is revolutionizing the way users approach technology across all industries. The 2018 revision of the European Energy Performance of Buildings Directive (EPBD) focused on promoting the adoption of smart technologies, in particular through the establishment of a smart readiness indicator (SRI). This indicator allows the assessment of the ability of buildings to adapt their operation to the needs of the occupant, including optimizing energy efficiency and overall performance, and adapting their operation in response to signals from the grid (energy flexibility). The SRI indicator should raise awareness among building owners and occupants of the value behind building automation and electronic monitoring of building technology systems, and should give occupants confidence in the actual savings that these new advanced features can bring. Although this definition of smart buildings refers primarily to energy issues, it is clear that smart ventilation is a key factor in the "smart" readiness of buildings, not only to reduce energy impacts but also to provide adequate air quality.

It is therefore more and more appropriate to equip an Air Handling Unit with an adequate technological infrastructure to make it a "smart" element of the plant. The starting point is certainly the monitoring of the environmental and operating conditions of the machine. Capturing information from as many sensors as possible to read information about indoor and outdoor air conditions and machine status provides a real-time understanding of how the unit and building are being used and how this changes over time. The knowledge of the state of occlusion of the filters, being able to monitor the hours of operation of the various devices, knowing the energy consumption of the fans, are fundamental sources of information if you want to conduct effective maintenance in line with the requirements of safety and hygiene as established by the standard VDI 6022.

Dashboards, trend charts, and alarm history provide the first level of aggregate information that can provide value to building managers, facility managers, or owners in making decisions. The second phase foresees the evolution of the AHU Control towards advanced logics and optimization. For example, understanding the level of contamination of environments through the acquisition of multiple environmental parameters (such as CO2, VOC, and PM 2.5-10) can highlight how they have different spatial and temporal trends. Basing the ventilation control on CO2 concentration alone may be generally insufficient, while basing the set point on a cumulative index of the different parameters may allow the ventilation system to be adapted so that each of these is always kept within predefined limits. These are just a few examples of the benefits that a suitable technological architecture can bring to the management of air systems.

5. CONCLUSIONS

Forced ventilation is the essential strategy to ensure that the air in confined spaces is adequate for health, comfort and safety. There is always an energy expenditure associated with it. Over the years, through standards, technologies and good building rules, it had been an objective to be pursued with particular care to achieve its optimization. The spread of the Sars-Cov2-19 pandemic, however, has forced a review of the scale of priorities in the design and operation of air treatment plants, which have been attributed an important role in the prevention of contagion in enclosed spaces. These new requirements imply a considerable increase in energy expenditure, which would be unsustainable and contrary to the principles of sustainability if these "new normal" conditions were to become frequent. In this report we show how the provision of technologies for heat recovery, indirect evaporative cooling, humidification and, more generally, the automation and supervision of the air handling unit in line with the most advanced hygiene standards, can be a solution to bring primary energy requirements back to an optimal situation, while still meeting stringent sustainability and safety requirements.

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Monograph: more than one author

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