Adaptation of HVAC Systems to Reduce the Spread of COVID-19 in Buildings

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Abstract: In 2020, all the world has been confronted with COVID-19. Bringing people together in buildings is proving to be a risk factor that we have to deal with. Although the greatest attention is paid to the SARS-CoV-2 virus, there are a number of other pathogens (viruses, bacteria, fungi, etc.) that can be transmitted through the air. These pathogens are sensitive to UV-C radiation. UV-C fluorescent lamps have been developed with technical parameters that are adapted to HVAC operating conditions. By using germicidal sources to disinfect the transported air, more than 90% of the SARS-CoV-2 virus, more than 97% of Influenza A virus, and 100% of Legionella pneumophila can be inactivated. The use of UV-C emitters for air disinfection allows the use of circulation and recuperation. Total balance of energy and CO2 emissions by variants and energies used, including humidification were performed for Slovak conditions. The operation of germicidal sources during the heating period in selected cities in our example would represent only 0.45% of the difference in heat demand and 0.42% of the difference in energy demand between operation according to recommendations and operation with germicidal sources. It is therefore an effective means of ensuring health safety and energy efficiency for the future.

Keywords: HVAC systems; COVID-19; recuperation; humidification; germicide emitter; UV-C fluorescent lamp

1. Introduction

After initial hesitation, the World Health Organization (WHO) confirmed that the SARS-CoV-2 virus, which causes disease COVID-19, is transmitted from humans to humans. In its document [1], it stated that if a patient with COVID-19 coughs or exhales air, he releases infectious droplets. The trick is that the patient with COVID-19 may be asymptomatic.

According to the information given in [2–5], if these droplets are large (100 μm), they settle on nearby surfaces within a few seconds. If they are smaller, they float in the air for a few minutes (10 μm) to several days (0.5 μm). Both surfaces and indoor air can thus become a source of SARS-CoV-2 virus infection. Even more seriously, the virus can thus infect people who have not been in direct contact with the primary source of infection at all (a person with COVID-19).

The WHO, as well as the countries confronted with COVID-19, have withdrawn from the initial hope that the pandemic will subside in several waves, and the general opinion is beginning to prevail that humanity will have to deal with the long-term existence of SARS-CoV-2.

At the time of reviewing this article (20 November 2020), the number of those infected worldwide has exceeded 57 million and the death toll approached 1,366,000. The average daily
increase overachieved 677,000 infected and a second wave of pandemic can be observed in many countries.

Although Slovakia was one of the least affected countries (in the first wave), the high international mobility of people poses for us a risk that is difficult to predict. Bringing people together in buildings (work, education, sport, culture, leisure, and trade) and in means of transport (travel) is proving to be a new risk factor that we have to deal with. Expectations of achieving community immunity by vaccinating the population against SARS-CoV-2 may not be realistic with the required high rate of pre-vaccination (more than 70% of the population) and increasing rejection of (other types of) vaccines. Therefore, other ways to reduce the risk of infection in the interiors should be considered.

Major professional associations in the field of heating, ventilation, air conditioning, and refrigeration systems (ASHRAE and REHVA) issued recommendations on how to operate HVAC systems already in the first months of the pandemic. The ASHRAE position document [6] was much more detailed than REHVA’s [7] and, most importantly, ASHRAE issued a number of recommendations for the operation of existing systems that are freely accessible. Both world-renowned professional associations mutually agreed that the ventilation and air filtration provided by HVAC systems can reduce the concentration of SARS-CoV-2 in indoor air, and thus reduce the spread of infection. In particular, ASHRAE pointed out that failure to modify internal conditions can cause heat stress in humans, which can directly endanger their health and also reduce their resistance to infection (p. 3) in [6].

The source of the virus is humans. Its concentration in the external environment is insignificant (it can only occur near people) as is written in [8]. Therefore, it is necessary to focus on the indoor environment.

The recommendations of the authorities of the professional community from the beginning of the pandemic can be summarized as follows:

- Prioritize and intensify natural ventilation;
- Increase the intensity of forced ventilation during the operating hours of the building and not switch it off outside the operating hours, but only reduce its intensity;
- Shut off air circulation;
- If the HVAC systems can handle this with their outputs, then also switch off heat/cold recovery from the exhaust air in the case of leaked heat exchangers;
- Keep HVAC systems clean and functional.

It was assumed that the peak of the pandemic would end in a “less energy-intensive time of the year”, which turned out to be unrealistic.

Shutdown of heat recovery or air circulation is associated with a significant increase in energy consumption for the operation of buildings and can cause serious problems in some new buildings in meeting the required parameters in the indoor environment (insufficient heating or cooling capacity). This measure therefore runs counter to efforts to reduce energy consumption, greenhouse gas emissions, and pollutants and to protect the environment.

It is worth noting what every 1000 m³/h of supplied outdoor air requires, e.g., in Bratislava, (capital of Slovakia) under the design conditions of HVAC equipment in the winter period, 14.50 kWh (outdoor temperatures −11 °C, indoor temperatures 20 °C) is required and in the summer period 3.20 kWh (outdoor temperatures 32 °C, indoor temperatures 26 °C) heat for treatment only of its temperature to the internal calculated temperature. The heat demand is even higher for the required air temperatures at the supply air outlets. For a total air output of 100,000 m³/h, this is an estimated increase in heat demand by 1858 MWh in winter and 77 MWh in summer at switching off the recuperation and circulation and at continuous ventilation (reduction outside the building’s operating hours to 50% of the ventilation output). In large building complexes, this increased heat demand, and therefore also energy demand, can be a significant item in operating costs.

ASHRAE provided [6] the following effective strategies to reduce the risk of SARS-CoV-2 infection in buildings:
a. Ventilation that dilutes the virus concentration and removes contaminated air to the exterior;
b. Suitable pressure difference between the spaces to prevent the transfer of contamination;
c. Optimization of fresh air supply (personalized ventilation);
d. Mechanical filtration;
e. Ultraviolet germicidal irradiation.

However, so far, all operational measures have focused on the initial recommendations from the beginning of the pandemic and neglected the use of germicidal irradiation (point e).

1.1. Systems of Using Germicidal Irradiation

Kowalski [9] stated that the first systems of using germicidal irradiation for air disinfection appeared already in 1930. At present, germicidal irradiation for air disinfection is used mainly in medical facilities, possibly in shelters and prisons [8], but it is not common in civil buildings. The extent of the use of germicidal irradiation in Slovakia is unknown.

There are several ways to use germicidal UV irradiation to disinfect the air, based on [10]:

1) Emitters in the uppermost 1/3 of the room;
2) Emitters aimed at heat exchangers or other surfaces in air handling units/distribution systems;
3) Emitters in the air flow in air handling units;
4) Portable circulating disinfection units.

(1) or (4) are suitable for spaces of infectious clinics, rooms, and operating rooms. Portable circulating disinfection units are devices that circulate air in a room through a HEPA filter and a chamber with a germicidal radiator. Radiation from the germicidal radiator remains in the chamber of the unit.

In the case of central air handling units, (2) and (3) are a suitable solution, while (2) rather serve to disinfect the surfaces of heating and cooling exchangers and are not effective enough to disinfect the transported air. Especially on cooling exchangers, water vapor condenses, thus creating conditions for the cultivation of pathogens. It does not have to be just bacteria and viruses, but it can be different types of algae and fungi.

The whole spectrum of UV radiation is divided into bands [9–11]:

- UV-A (315 to 400 nm);
- UV-B (280 to 315 nm);
- UV-C (100 to 280 nm) while from 100 to 200 nm it is a vacuum UV.

Due to the fact that pathogens (their DNA or RNA and proteins) absorb UV-C radiation well, which at a sufficient dose disrupts the binding of DNA components or RNA and thus causes their inactivation, this radiation can be used to disinfect air, water, and surfaces. Currently, it is most often used to disinfect surfaces (tools and aids in healthcare) and water.

According to different expert sources, e.g., [12–14], radiation with a wavelength of 265 nm is most effective. Fluorescent UV-C emitters have a maximum radiant flow at a wavelength of 253.7 nm. Viruses are among the most sensitive pathogens. A by-product of UV-C radiation with a wavelength of 185 nm is ozone, which is a strong oxidant and it is not desirable to accumulate it in areas where people move, because its higher concentrations are harmful to health. Therefore glass, which absorbs radiation of this wavelength, is used for germicidal fluorescent lamps for air disinfection. UV-C radiation is dangerous to people’s eyes and skin. In addition, it accelerates the degradation of some materials (e.g., filters, seals, etc.). Therefore, direct exposure of humans and sensitive materials should be avoided.

1.2. Pathogens Rate

Although the greatest attention is currently paid to the SARS-CoV-2 virus, there are a number of other pathogens (viruses, bacteria, fungi, etc.) that can be transmitted through the air. Every year there are more emerging, e.g., seasonal epidemics of influenza, which, in addition to incapacity for work, also cause casualties. All of these pathogens are sensitive to UV-C radiation.
How the pathogen is sensitive to UV-C radiation is expressed by an inactivation rate constant \( k \) \([m^2/J]\). This constant depends on the type of pathogen and the environment in which it is located (it has different values for air, surfaces, and water). Values for some selected pathogens in the air are in Table 1.

**Table 1. Inactivation rate constant for selected types of pathogens in air [9,11].**

| Pathogen                | \( k [m^2/J] \) |
|-------------------------|------------------|
| *Escheria coli*         | 0.09270          |
| Influenza A             | 0.11870          |
| *Legionella pneumophila*| 0.44613          |
| *Mycobacterium tuberculosis* | 0.09870       |
| SARS-CoV-2              | 0.08528          |
| *Staphylococcus aureus* | 0.34760          |
| Streptococcus pyogenes  | 0.10660          |
| *Vaccinia virus*        | 0.15280          |

Assuming a single-stage pathogen extinction model, their survival rate after irradiation is expressed by formula

\[
S = e^{-k \cdot \text{DUV}} \quad [\%],
\]  

where DUV is the radiation dose \([J/m^2]\).

Complement to survival rate \( S \) is the rate of pathogen inactivation

\[
\eta = 1 - S.  \tag{2}
\]

The theory of pathogen inactivation also knows more complicated models, see, for example, [9], but for basic information this model is sufficient. Using the value of \( k \) from Table 1 for SARS-CoV-2 assumes that at an irradiation dose of 27 J/m², 10% of the viruses survive and 90% are inactivated. A dose of 19.40 J/m² is sufficient to inactivate 90% of Influenza A and a dose of 5.16 J/m² is sufficient for *Legionella pneumophila*. It is clear that other pathogens are also inactivated in an environment that inactivates SARS-CoV-2.

The irradiation dose is the result of the time \( t [s] \) of the pathogen’s movement in the radiation field and the radiation intensity \( I [W/m^2] \)

\[
\text{DUV} = I \times t \quad [J/m^2]. \tag{3}
\]

The time \( t \) depends on the air flow rate and the path length of the pathogen in the radiation field. Therefore, when designing air disinfection, it is necessary to ensure a sufficiently long time or long path of the entrained pathogen in the radiation field. The faster is its movement, the longer must be the time or the path or the larger must be the radiation intensity.

When designing air disinfection by UV-C radiation, it is necessary to know the radiation field or the space, which is generated by germicidal sources and which is characterized by the intensity of radiation \( I [W/m^2] \) at each of its points, as well as the speed of air flow in [m/s] and the path of the pathogen [m].

### 1.3. Fluorescent UV-C Technology for HVAC

For applications in air handling units, UV-C fluorescent lamps have been developed with higher efficiency, but mainly with technical parameters that are adapted to HVAC operating conditions. UV-C radiation is a very efficient and cost-effective way of disinfecting air and air ducts or filters, but only if the costs of servicing and renewing the UV-C system do not exceed the planned savings. UV-C fluorescent lamps for HVAC have been specially manufactured and modified. We divide them according to the types of sockets (2-pole or 4-pole), length (from 100 to 1495 mm), glass specification (without ozone or with ozone production), and glass structure (tube) for dry areas with one wall, for immersion radiators with two walls, or made of quartz thermo glass with two walls. Each of these
lamps has its own characteristic efficiency curve and temperature/power ratio and IP protection specification. All fluorescent systems are designed for a minimum for 9000 operating hours (<90% of the original efficiency), but in many applications they can be operated continuously for two years.

The UV-C system in HVAC is usually in operation for almost the whole year and we design its service life for 100,000 operating hours. Fluorescent lamps are consumables. The optimal lamp replacement cycle is determined by their effective life from 9000 to 25,000 operating hours, when the efficiency in the UV-C spectrum range must not fall below 90%. In addition to the decreasing efficiency of the TUV lamp (tubular UV lamp) itself, the efficiency of the system is also affected by air temperature, dust pollution, and degradation of reflective surfaces in the ventilation ducts. Even with regular maintenance and cleaning, it is necessary to take into account a reduction in the efficiency of the system within service cycles in the range from 10% to 35%, depending on how the system is built and operated. If we need the available power of 8 x 30 W in UV-C in the part of the spectrum 254 nm and take into account the factors reducing efficiency within one cycle of lamp replacement up to 38%, then we use a standard TUV lamp system 8 × TUV 64T5 HO 4P SE UNP/32 (Figure 1) without ozone production with four-pin single ended sockets with a power input of 145 W with power in UV-C after 100 h of operation 8 × 45 W with an adjustable ballast according to the CRO system—constant radiation output.

![Figure 1. Tubular UV (TUV) source 64T5 HO 4P SE UNP/32 145 W.](image)

Constant radiation output method is a method that achieves the same radiation power in the UV-C range from a single source using controllable high-frequency ballast. Each ballast can be set for the life cycle of the TUV lamp according to its prescribed effective life or switching cycles. For example, 1000 starts of a fluorescent lamp will shorten its life to 10%. The ballast calculates the number of operating hours and, according to a pre-set power curve, determines the wattage of the fluorescent lamp at the beginning and at the end of the lamp life so that the UV-C power may be constant. At the same time, if a fluorescent lamp with amalgam technology is used, we are able to regulate the operating power of the fluorescent lamp during the operating time of 9000 h in the range from 40% to 100% of its nominal power. In this way, we achieve an extension of the effective life of about 15% and a constant performance in the UV-C range with excellent energy efficiency of the system as a whole. In practice, we are talking about hundreds of saved kWh on the consumption of electric power by system CRO. The long life of fluorescent lamps is a key factor in the economic return of the UV-C system.

Fluorescent lamps with amalgam technology of temperature stabilization depending on temperature and service life are used for HVAC. The main goal is for the performance in the UV-C range to be around 90% at 9000 operating hours and an ambient temperature of 25 °C. If standard T8 fluorescent lamps were used, the efficiency in the UV-C region of the spectrum would fall below 70% and the reduction in power in the UV-C region would be very large. To illustrate, if a fluorescent lamp were operated in an ambient environment with an air temperature of 8 °C and an air flow of 1 m/s, its efficiency would be about 35% in the UV-C range. The pressure in the mercury vapor
discharge depends very much on the cooling rate of the discharge and the condensation of the mercury vapor in the cold places of the fluorescent lamp.

Each air handling unit even within one building has different operating modes, outputs, and purpose. Depending on the environment and operating conditions, the UV-C system is designed and adapted, e.g., for air conditioning for wellness, common areas, kitchens, restaurants, smoking rooms, rooms, and garages.

The basic parameter in the design is the effective dose in the UV-C spectrum; all other technical parameters must be variably dimensioned. It is not possible to use conventional T8 fluorescent tubes for HVAC applications, although their efficiency is very good. We need fluorescent lamps with smaller dimensions and higher specific power per cm² of lamp body area. This is so that we may be able to minimize the resistance of the air flow and at the same time the mechanical effects on the fluorescent lamps themselves.

Various vibrations are caused in the air conditioning ducts by fans and flowing air, as well as a rapid change in temperature from 4 to 35 °C, condensation of vapors, dust, and mold.

This is a challenging environment for fluorescent technology. Similarly, problems would occur if we left the fluorescent lamps exposed to the external environment. Each lamp starts at a high voltage from 1 kV to 4.4 kV, which in cases of high humidity or sudden condensation in the air conditioning causes a breach of the insulation of the sockets and electrical breakdowns cause damage to the entire UV-C system, including ballasts. Often due to electrical short-circuits caused in this way, the entire HVAC system is taken out of operation. Even for these risk situations, systems with IP 55 or up to IP 68 protection are designed for wellness or restaurant areas. The cover is provided by a protective tube made of quartz glass, closed on one side.

This mechanical protection of the fluorescent lamp is also a thermal insulation of the discharge in the fluorescent lamp. To maximize efficiency, a range of operating temperatures is specified for each lamp. In the area of air conditioning, the surface temperature of the lamp ranges from 25–40 °C. If thermal quartz glass with a high UV-C transmission is used, as well as with an air flow of 8 °C, the ambient temperature of the fluorescent lamp is stabilized. For optimal operation of the fluorescent lamp, it is important that in the event that the air flow stops, for example when the air conditioning is switched off, the UV-C system is also switched off or its output is reduced by dimming the ballasts to the minimum possible.

The core of the UV-C system in HVAC is still the UV-C fluorescent source. They provide optimal performance. For the design of a UV-C fluorescent system, it is necessary to know the operating parameters of the air-conditioning system and the machine. It is best if there exist measurements or diagnostic data on operation during summer and/or winter. Depending on the boundary conditions, an efficient and effective UV-C system can be designed with low operating costs. If a good project has been done and implemented correctly, the service life of the UV-C system exceeds the service life of the air handling unit.

2. Materials and Methods

The calculation was performed for Slovakia, the capital city of Bratislava (Figure 2 and Table 2). We virtually used, for a general administrative building, an air-conditioning unit with a capacity of 24,000 m³/h with an accessible air-conditioning pipe measuring 1600 × 700 mm. The unit has a circulation and recuperation section and is designed so that the average air flow velocity in the accessible air duct is 6 m/s and the length. Available for installation is a free length of air duct 2 m.
As an example of the design of an additional installation of germicidal emitters, we used an air conditioning unit for our condition in the following steps:

- Determination of the course of air temperature and relative humidity of the reference day in the assessed month of summer and winter (Figure 3).
- Determination of the required indoor air parameters. For summer 24 °C, relative humidity 40%, for winter 22 °C, relative humidity without treatment.
- Definition of the operating mode for Variant 1 and Variant 2 (Figure 4).
- The simulation calculation was always performed for the reference day in the given month. The calculation was calculated with an hourly step, for each calculated quantity.
- Input parameters have been changed for calculation variants and alternatives.
- To determine the influence of germicidal sources, a mathematical calculation of the radiation of the flowing air in the ventilation ducts was performed. The simulation declared the most advantageous position of the UV tubes. The required power input of the tubes was taken into account in the energy balance.
- Calculations were evaluated from an energy point of view, using different types of energy sources. The environmental impact was calculated according to the coefficients in [15] for the Slovak Republic.
Figure 3. The course of air temperature and relative humidity of the reference day in the assessed month of summer and winter.

Figure 4. Time course of ventilation and air conditioning operating modes for working and free day.
We analyzed 3 design alternatives:

A. UV-C emitters placed parallel to the air flow—3 rows of 4 emitters with centers in the middle of the free length of the pipe,

B. UV-C emitters placed perpendicular to the air flow—2 rows perpendicular to each other at a distance of 0.5 m from each other, the extreme row always 0.75 m from the limit of the free length of the pipe (6 vertical emitters and 4 horizontal),

C. UV-C emitters placed perpendicular to the air flow—2 on mutually parallel rows at a distance of 0.5 m from each other, the extreme row always 0.75 m from the limit of the free length of the pipe (6 + 5 vertical emitters).

In all alternatives, the use of tubular UV-C fluorescent lamps with ozone-reducing glass (filtering the wavelength of 185 nm) and covering the inner walls of the free section of the ventilation duct with aluminum foil with a UV-C reflectance of 0.73 was envisaged.

The parameters of the installation alternatives are in Table 3.

The $D_{UV}$ radiation dose and inactivation rate $\eta$ curves are shown in Figures 5 and 6 (alt A), Figures 7 and 8 (alt B), and finally Figures 9 and 10 (alt C).

Comparison of parameters of installation alternatives is in Table 4

### Table 3. Parameters of UV-C emitters.

| Sources      | Quantity | Power supply [W] | Power consumption [W] |
|--------------|----------|------------------|-----------------------|
| Horizontal   | 12       | 12               | 60                    |
| Vertical     |          | 6                | 28                    |
| Completely   | 12       | 228              | 720                   |

### Table 4. Comparison of installation alternatives.

| Min | Max |
|-----|-----|
| $\eta$ [%] | $D_{UV}$ [J/m²] | $\eta$ [%] | $D_{UV}$ [J/m²] | $\eta$ [%] | $D_{UV}$ [J/m²] |
|-----|-----|-----|-----|-----|-----|-----|
| 64.19 | 12,041 | 68.39 | 13,505 | 68.98 | 13,728 |
| 90.53 | 12,695 | 92.20 | 31,303 | 93.23 | 33,369 |
| 91.48 | 30,683 | 93.15 | 32,376 | 94.15 | 34,491 |
| 91.86 | 29,412 | 93.94 | 32,875 | 94.99 | 35,098 |
| 99.92 | 82,926 | 96.82 | 40,417 | 96.99 | 41,072 |

std: 31.57% , 16.90% , 17.80%
**Figure 5.** The DUV radiation dose—Alternative A.

**Figure 6.** The inactivation rate $\eta$ curves—Alternative A.

**Figure 7.** The DUV radiation dose—Alternative B.
Figure 8. The inactivation rate $\eta$ curves—Alternative B.

Figure 9. The DUV radiation dose—Alternative C.

Figure 10. The inactivation rate $\eta$ curves—Alternative C.
The value of avg is the arithmetic mean of the values at the individual points of the network (33 × 15 points) and avgₚ is the weighted average by the area of the segment belonging to each point (network modulus 0.05 × 0.05 m).

The individual alternatives were comparable as a result, while the highest rate of inactivation was shown by alt. C and the greatest uniformity alt. B. The electrical inputs of the germicidal power supply systems ranged from 720 to 957 W.

The application of germicidal sources can significantly affect the energy intensity of the operation of air conditioning systems. For this purpose, we prepared a year-round balance sheet recalculation for the Bratislava area for an administrative building. The outdoor air temperature profiles are shown in Figure 11. The comparative operation is according to the recommendations of ASHRAE resp. REHVA.

![Figure 11. Course of average daily air temperatures during the year used in the calculations.](image)

Variant 1—according to ASHRAE, on a working day, the building is operated for 12 h with 100% output for fresh air, without circulation and without recuperation. Other times, the output is reduced to 50%.

Variant 2—using germicidal sources, with the start of the system 2 h before the start and 2 h after the end of the building operation. The fresh air dose is 30% using circulation and air recuperation with an efficiency of 80%. The germicidal power supply is switched on at full power of 822 W during the entire operation of the air handling unit.

We have included in the balances an alternative without humidification and with humidification of the supplied air in winter operation. The air output of the air handling unit is 24,000 m³ h⁻¹; the electrical input of the fans is 20.6 kW. During ventilation (May and September) the air is not heated and cooled, only the air is exchanged. Only heating/cooling energy was included in the calculations to reach the required supply air temperature of 22 °C in winter and 24 °C in summer. Other heat losses resp. gains did not figure in the calculation.

3. Results

Year-round operation calculations for variant 1 with humidification are shown in Table 5 and Figure 12 for operation by ASHRAE, and for variant 2 in Table 6 and Figure 13 for operation using germicidal emitters.
Table 5. Energy demand for air conditioning operation according to ASHRAE with humidification according to variant 1.

| ENERGY NEED—ASHRAE OPERATION | Heating kWh | Cooling kWh | Humidification kWh | Fans kWh | Together kWh |
|-----------------------------|-------------|-------------|-------------------|---------|--------------|
| Months                      |             |             |                   |         |              |
|                            | -           | -           | -                 | -       | -            |
| 1                           | 110,135     | 43,990      | 9677              | 163,801 |
| 2                           | 83,188      | 36,591      | 8755              | 128,534 |
| 3                           | 69,445      | 29,690      | 9562              | 108,697 |
| 4                           | 44,054      | 19,057      | 9216              | 72,326  |
| 5                           | -           | -           | 9562              | 9562    |
| 6                           | -           | 12          | 9216              | 9228    |
| 7                           | -           | 1617        | 9677              | 11,293  |
| 8                           | -           | 1322        | 9562              | 10,884  |
| 9                           | -           | -           | 9331              | 9331    |
| 10                          | 47,088      | 21,130      | 9792              | 78,011  |
| 11                          | 70,798      | 29,839      | 9216              | 109,854 |
| 12                          | 92,476      | 36,394      | 9331              | 138,202 |
| Sum                         | 517,185     | 2951        | 216,691           | 849,722 |
|                             | 60.9%       | 0.3%        | 25.5%             | 13.3%   | 100%         |

Table 6. Energy demand for air conditioning operation using germicidal sources with humidification according to variant 2.

| Energy Need—UV Disinfection Operation | Heating kWh | Cooling kWh | Humidification kWh | Fans kWh | UV Disinfection kWh | Together kWh |
|---------------------------------------|-------------|-------------|--------------------|---------|---------------------|--------------|
| Months                                |             |             |                    |         |                     |              |
| Sum                                   | 19,954      | 725         | 44,113             | 76,800  | 3,288               | 144,880      |
|                             | 13.8%       | 0.5%        | 30.4%              | 53.0%   | 2.3%                | 100%         |

Figure 12. Graphic representation of the course of energy consumption according to ASHRAE with air humidification according to variant 1.
Figure 13. Graphical representation of the course of energy consumption using germicidal sources with air humidification according to variant 2.

Comparisons of variants declared energy consumption for air conditioning operation V1 = 348.2 MWh, V2 = 58.2 MWh, which is a difference of 289.8 MWh expressed as a percentage of 83.3%.

Calculations for year-round operation for variant 1 without humidification are shown in Table 7 and Figure 14 for ASHRAE operation, and for variant 2 in Table 8 and Figure 15 for operation using germicidal sources.

Table 7. Energy requirement for air conditioning operation according to ASHRAE without humidification according to variant 1.

| Months | Heating kWh | Cooling kWh | Humidification kWh | Fans kWh | Together kWh |
|--------|-------------|-------------|--------------------|---------|--------------|
| 1      | 110,135     | -           | 9677               | 119,812 |
| 2      | 83,188      | -           | 8755               | 91,943  |
| 3      | 69,445      | -           | 9562               | 79,007  |
| 4      | 44,054      | -           | 9216               | 53,270  |
| 5      | -           | -           | 9562               | 9562    |
| 6      | -           | 12          | 9216               | 9228    |
| 7      | -           | 1617        | 9677               | 11,293  |
| 8      | -           | 1322        | 9562               | 10,884  |
| 9      | -           | -           | 9331               | 9331    |
| 10     | 47,088      | -           | 9792               | 56,880  |
| 11     | 70,798      | -           | 9216               | 80,014  |
| 12     | 92,476      | -           | 9331               | 101,808 |
| Sum    | 517,185     | 2951        | 0                  | 633,032 |
|        | 81.7%       | 0.5%        | 0.0%               | 17.8%   | 100%         |

Table 8. Energy demand for air conditioning operation using germicidal sources without humidification according to variant 2.

| Months | Heating kWh | Cooling kWh | Humidification kWh | Fans kWh | UV Disinfection kWh | Together kWh |
|--------|-------------|-------------|--------------------|---------|--------------------|--------------|
| 1      | 4536        | -           | 6758               | 289     | 11,583             |
| 2      | 3360        | -           | 6144               | 263     | 9767               |
| 3      | 2619        | -           | 6451               | 276     | 9347               |
| 4      | 1544        | -           | 6144               | 263     | 7951               |
| 5      | -           | -           | 6451               | 276     | 6727               |
| 6      | -           | 3           | 6144               | 263     | 6410               |
| 7      | -           | 402         | 6758               | 289     | 7450               |
| 8      | -           | 320         | 6451               | 276     | 7048               |
| 9      | -           | -           | 6451               | 276     | 6727               |
Comparisons of variants declared energy consumption for air conditioning operation $V_1 = 257.9$ MWh, $V_2 = 39.8$ MWh, which is a difference of 218.1 MWh expressed as a percentage of 84.6%.

In real conditions, heat and cold for heating are provided by various sources. The impact on primary energy and CO₂ emissions is also defined accordingly. Electricity (EE) is used to drive fans and UV germicidal sources. Heat pump with electric drive is used for cold production. Humidification of air is realized by water vapor with the help of gas or electricity. Heat production for heating is by gas, heat pump, or electricity. The energy conversion efficiencies are given in Figure 16 and are taken into account in further calculations in Figures 17–22. We used the factors of primary energy and CO₂ emissions for conversion according to [16] for Slovakia.
### Figure 16. Energy conversion efficiencies in the devices considered in the calculation.

| Energy used       | Input energy | Conversion efficiency |
|-------------------|--------------|-----------------------|
| Heat              | Gas          | 0.95                  |
|                   | 2 RES        |                       |
|                   | 3 Electricity - HP drive | 3.5                  |
|                   | 4 Electricity - heating | 0.99                |
| Cold              | 5 RES        |                       |
|                   | 6 Electricity - HP drive | 2.7                  |
| Humidification    | 7 Gas production | 0.95                |
|                   | 8 Electricity production | 0.99               |
| Fan               | 9 Electricity drive | 0.99                |
| UV disinfection   | 10 Electricity radiation | 0.99              |

### Figure 17. Variant 1—operation according to ASHRAE—heat supply from gas.

![Energy conversion diagram for Variant 1—operation according to ASHRAE—heat supply from gas.]

### Figure 18. Variant 1—operation according to ASHRAE—heat supply from the heat pump.

![Energy conversion diagram for Variant 1—operation according to ASHRAE—heat supply from the heat pump.]

### Figure 19. Variant 1—operation according to ASHRAE—heat supply from electricity.

![Energy conversion diagram for Variant 1—operation according to ASHRAE—heat supply from electricity.]

4. Discussion

Total balance of energy and CO$_2$ emissions by variants and energies used, including humidification, is listed in Figure 23.
The supplied energy is directly consumed taking into account the conversion efficiency (boiler, heat pump, humidification, etc.). Operation without humidification is no longer listed in Figure 22. Primary energy is the product of the supplied energy and the primary energy coefficient.

- Comparison of supplied energy Variant 1-1 (889.49 MWh/year) and Variant 2-1 (149.06 MWh/year) difference is savings = 740.43 MWh/year = 83.2%. When comparing, CO₂ savings = 85.0%.
- Comparison of supplied energy Variant 1-2 (853.05 MWh/year) and Variant 2-2 (146.13 MWh/year) difference is savings = 706.92 MWh/year = 82.9%. When comparing CO₂ savings = 72.7%.
- Comparison of supplied energy Variant 1-3 (858.28 MWh/year) and Variant 2-3 (146.34 MWh/year) difference is savings = 711.94 MWh/year = 82.9%. When comparing CO₂ savings = 83.0%.

In each comparison between Variant 1 and Variant 2, the calculation declared an energy saving of about 83%. Compared to CO₂, the savings are at the level of about 80%.

In the case of a longer operating time of the building, the absolute savings would be even greater. As a percentage, we can consider savings similar regardless of operating time.

5. Conclusions

By additional installation of germicidal sources in the ventilation ducts, the place of air disinfection can be brought closer to the place of its supply to the supplied interiors and thus decentralized. This will reduce the risk of reactivation of pathogens during air transport after central disinfection, simplify the design of UV-C sources (lower air flow rates, lower power requirements, and smaller piping dimensions) and increase operational safety (lower probability of disinfection failure throughout the whole building).

By using germicidal sources to disinfect the transported air, more than 90% of the SARS-CoV-2 virus produced by humans in internal environment can be inactivated. At the same time, more than 97% of Influenza A virus and 100% of *Legionella pneumophila* could be inactivated.

According to many professionals [17–25], changing the air to the outside air once an hour will reduce the contamination of the indoor air to 37% of the original concentration and exchanging the air three times per hour will reduce it to 5% of the original concentration. The use of UV-C emitters for air disinfection allows the use of circulation and recuperation even in the conditions of measures to prevent the spread of SARS-CoV-2.

The operation of germicidal sources during the heating period in Bratislava conditions in the above example would represent only 0.45% of the difference in heat demand and 0.42% of the difference in energy demand between operation according to ASHRAE and REHVA recommendations and operation with germicidal sources. It is therefore an effective means of ensuring health safety and energy efficiency.

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