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Air Filtration and Sterilization in Ventilation Systems According to the New Paradigm

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ABSTRACT

The paper deals with the subject of increasing the efficiency of air purification in ventilation systems in situations of unusual hazardous indoor air pollutants. It analyzes possible locations of additional filtering and sterilizing elements in the installation to eliminate their return to the rooms. The quantities of pollutants in particular parts of the system were determined for a given fan configuration in the air handling unit and a possible leakage in the heat recovery system. Guidelines were proposed for the design and construction of systems to enable rapid modification of systems in the event of unusual contamination or pathogens in the indoor air.

Keywords: pathogen, filtration, ventilation, indoor air pollution, indoor air quality, COVID-19, SARS-CoV-2, air handling unit

INTRODUCTION

The SARS-CoV-2 pandemic should inspire a new, different approach to the design standards for ventilation and air conditioning systems (HVAC) especially in buildings that are not health care facilities. They should give the possibility of rapid modification of installations in order to eliminate hazards or at least not increase them. Therefore, it is proposed to take a new paradigm and introduce appropriate guidelines and later regulatory changes for the design and operation of HVAC systems. Support for this postulate can be found in [12a, 12b].

Many institutions during the pandemic indicated emergency measures to improve the functioning of ventilation systems due to the risk of airborne transmission of the pathogen: ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) [1] and REHVA (the Federation of European Heating, Ventilation and Air Conditioning Associations) [18] based on existing evidence of the airborne transfer. There are many more guidelines from different organizations concerning ventilation, e.g: EUROVENT MIDDLE EAST [8], CIBSE (The Chartered Institution of Building Services Engineers) [4], SHASE (the Society of Heating, Air-Conditioning and Sanitary Engineering in Japan) [23], ECDC (European Centre for Disease Prevention and Control) [7], the German Association of Indoor Ventilation Technologies [24], San Francisco Department of Public Health [21]. There are also further updates and new guidelines, e.g: REHVA [15–17, 19], ASHRAE [2], website of the Centre for Disease Prevention and Control. There are also reviews of these guidelines [9, 22] and research and simulations highlighting the importance of well-functioning ventilation to reduce the spread of SARS-CoV-2 [3b, 13].

This topic was also previously raised by the authors in [3a, 3b, 3c]. This article is intended to develop and detail the above-mentioned guidelines and previous works of the authors, because it is also necessary to put emphasis on increasing the awareness of hazards among manufacturers, contractors and technical services responsible for the production, construction, proper installation, start-up and operation of ventilation systems.

There is a need for a different perspective on the design of ventilation systems according to a new paradigm [12a]. The purpose and novelty of the paper is: (i) discussion of benefits and problems resulting from possible locations of air filtration or sterilization elements in the ventilation system; (ii) proposal of solutions giving the possibility of fast modification according to the appearing danger (selection of fans, special and additional sections of air handling units allowing installation of different types of filters); (iii) indication of recommended solutions for future design.

MATERIALS AND METHODS

Air filters in ventilation systems and their ranges of operation

Air filters are used for cleaning the outdoor and circulating air in ventilation systems and are designed to stop solid contaminants of low concentrations, generally less than 5 mg/m^3.

Generally filters are divided into [5, 6]:

- coarse – 1st filtration stage,
- fine – 2nd filtration stage,
- EPA (Efficiency Particulate Air) – high efficiency of filtration – 3rd filtration stage,
- HEPA (High Efficiency Particulate Air) – very high efficiency of filtration – 3rd filtration stage,
- ULPA (Ultra Low Penetration Air) – very high efficiency of filtration – 3rd filtration stage.
- special (carbon, electrostatic, ionization, UV lamps, etc.) – additional filtration or sterilization, odor removal.

Mechanical ventilation and air conditioning units and their individual components should be protected against pollutants in the outdoor air and, in special cases, in the recirculated (re-circulated) air, using filters [14]:

- heaters, coolers and heat recovery units – at least G4 class,
- humidifiers – at least class F6, as specified in the polish standard for classification of air filters.

In practice, in ventilation and air conditioning units, the following filter combinations are used:

- rooms without air cleanliness requirements – simple ventilation devices: coarse dust filter,
- rooms with increased air cleanliness requirements: coarse dust filter + fine dust filter;
- rooms with special requirements for air purity, e.g. clean rooms (in hospitals): coarse filters + fine filters + high efficiency filters.

The selection of filters should be made after the analysis of contaminants of the filtered air and determining the required class of air cleanliness in the room [10]. The selection of the proper filters is based on the determination of their characteristics, class and design, as well as their surface area. Pressure drop ranges and expected operating times for each filter type are given in the table 1 below. The service life of the filters depends on the purpose of the installation and filtered air cleanliness and typically varies from 0.5 to 2 years.

Additional air purification in ventilation systems

In addition to the general rules described above for the selection and installation of filters in ventilation systems, the updated/new standards should take into account the possibility of replacing them with more effective ones, or equipping the system with additional cleaning devices. As a result of the recent SARS-CoV-2 pandemic, it is expected that new filtration technologies will be researched to increase the efficiency of stopping, for example, coronavirus and other pathogens in the future [11].

Replacing a traditional filter with a HEPA-type filter will cause some problems, because it should be remembered that the higher the class of filter, the higher its airflow resistance. Classical filters, which are able to stop contaminants or pathogens with efficiency close to 100%, cause significant pressure losses, which in normal installations will significantly reduce the air flow.

To be able to replace classical filters with more precise and efficient ones, it is necessary to

Table 1. Types, pressure losses and service life of air filters

Filter type	Pressure loss		Service life expectancy, week
	Initial, Pa	Final or max, Pa	
Coarse filter	30–50	250 [6]	12–24
Fine filter	50–150	450 [6]	20–36
EPA, HEPA ULPA filter	100–250	400–750	24–72

provide for a certain overpressure in the fan in order to maintain the design air flow in the installation. The measures used should not reduce this flow rate. We may also consider the possibility of replacing the fans or their engines with more efficient ones in order to maintain the air stream – but these actions are more expensive and will more time.

An alternative to the above may be solutions that cause smaller pressure drops and do not cause such a problems with reduction of air flow:
- ducted electrostatic filters,
- ducted devices with UVc lamps, in particular those producing H_2O_2 to inactivate the virus,
- ducted air ionizers.
- ion generators.

When using this type of equipment, it must be taken into account that it can generate substances (e.g. H_2O_2, O_3) or agents (UV radiation) that are hazardous to health. Therefore, they must be used in a way that prevents people from being exposed to these factors to a degree that would endanger them.

Methodology of calculations

The methodology of calculations of returning contaminants ratio where based on equations as below. The impact of the filters in particular locations was calculated as follows:

$$C_{AF} = (1 - \eta) \cdot C_{BF} \tag{1}$$

where: C_{AF} – contaminant concentration in air stream after filter,
C_{BF} – contaminant concentration in air stream before filter,
η – filter efficiency.

The C_{AL} after leak was calculated as follows:

$$C_{AL} = \frac{C_{BL} \cdot \dot{V}_{BL} + C_{leak} \cdot \dot{V}_{leak}}{\dot{V}_{BL} + \dot{V}_{leak}} \tag{2}$$

where: C_{leak} – contaminant concentration in air leak,
$\dot{V}_{leak}$ – volume flow of air leak, m^3/h
C_{BL} – contaminant concentration in air before leak,
$\dot{V}_{BL}$ – air volume flow before leak, m^3/h

and air flow after the leak:

$$\dot{V}_{AL} = \dot{V}_{BL} + \dot{V}_{leak} \tag{3}$$

Recirculated part of contaminants to particular air streams was defined as:

$$CR_i = \frac{C_i}{C_{ETA}} \tag{4}$$

where: C_i – contaminant concentration in particular air stream,
i – air stream indicator: EHA (exhaust air), ODA (outdoor air), ETA (extract air), SUP (supply air),
C_{ETA} – contaminant concentration in extract air.

Supply and extract airflows $\dot{V}_{SUP}$, $\dot{V}_{ETA}$ rates were taken as constant values independent of leaks in the air handling unit.

The filter location in the installation

Undesirable particles that may spread in the air are various pathogens (bacteria, viruses, protozoa, fungi, mold), biological pollutants (pollen causing e.g. allergies, asthma), and chemical (e.g. formaldehyde emitted by the elements of interior design or products of metabolism) or physical (e.g. various fractions of PM) both of internal and external origin. The role of ventilation systems should be to remove or dilute these pollutants in indoor air to an acceptable, safe level.

The location of purification or sterilization elements depends on location of the source of potential contaminants or pathogens. With the influx of pollutants into the ventilation system from outside, the question of the location of the filter is obvious, but with the source of pollution in the room and the leaks in the air handling unit, the situation becomes more complicated.

We indicated favorable location of the air-purifying element or device in the ventilation system considering general pros and cons of particular locations and calculations of recirculated contaminants ratio, with the source of pollution in the room and the leaks in the air handling unit. Figure 1 shows where air filters, sterilizers, or air purifiers may be located in a ventilation system serving a one room or group of rooms. The colors

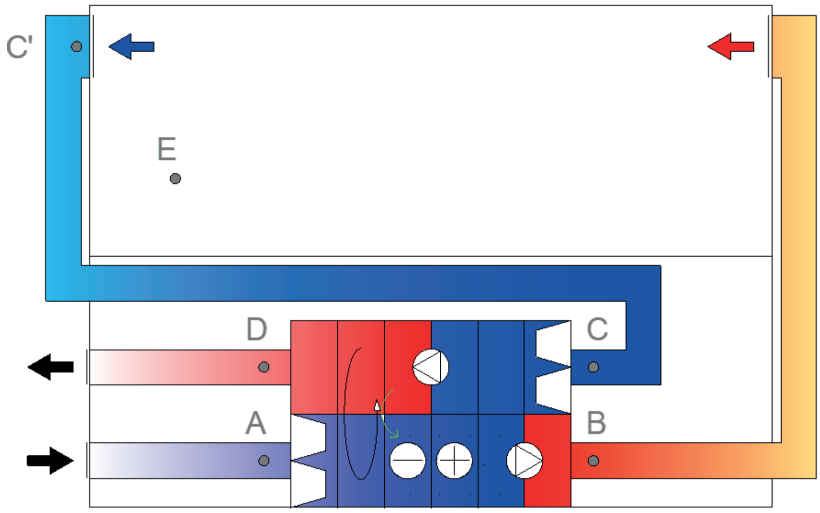

Figure 1. Locations of air cleaning devices (A, B, C, C', D, E).

represent changes in pressure in the air handling units and in the ducts, and the variation in the shades symbolizes the variation in its value (the more intense the color, the higher the absolute value of the pressure). The blue color represents negative pressure, the red color represents positive pressure and the white color represents atmospheric pressure.

General pros and cons of particular locations of additional filters

When the presence of a contaminant or pathogen in the supply or exhaust air cannot be eliminated, the one of the solution is to use high-efficiency filters on the appropriate air flow. If the threat is external whether in the form of dust, or other types of pollution, or pathogens, appropriate quality and type of filter on the outdoor air should solve the problem. The situation is different when the pollution occurs in the room (e.g. the source is a sick person or some process and local ventilation is not 100% effective) and its high concentration can threaten the users. Then, depending on the case, it is necessary to consider installing filters in different parts of the system. There is a possibility to install it in supply air duct – after the air handling unit (Figure 1 location B), in extract air duct – before the air handling unit (Figure 1 location C) or just after the room (Figure 1 location C'), in extract air duct (Figure 1 location D) or in the room (Figure 3 location D) [3a]:

- Locating such a device in the extract duct (Figure 1, location C or C') is associated with cleaning the air containing the most contaminants. For a given efficiency, the amount of uncaptured contaminants by a filter placed in the extract duct will be much greater than if it were placed in the supply duct.
- Regarding potential leaks, the location of the extract air filter close to the room prevents the flow of polluted air throughout the entire extract system. At the same time, a significant reduction in the pollution of the exhaust air to the outside of the building is achieved and may eliminate the possible need to relocate the intake and/or exhaust air outlets.
- Additionally, the purification element in the extract duct (Figure 1, location C or C') is in the negative pressure zone, thus avoiding leakage of polluted air outside the installation.
- On the other hand, the location of a purification device with significant air flow resistance (e.g., filter) on the extract duct directly after the room (Figure 1, location C') increases the negative pressure in the entire extract system and intensifies the suction of air through leaks into the ducts leading through rooms and polluted zones.
- In the case of a potential leakage from the extract air into the supply air, the location of the purification element in the supply air duct in a high overpressure zone increases the risk of polluted air escaping from outside the unit.
- The argument for installing a purification device in a supply duct is to ensure the filtration of contaminated air from outside in the case of an unfavourable position of the outdoor intake and exhaust air outlet (e.g., blocked devices).

The filters and the above-mentioned devices can also be installed on the by-pass duct [3a], with an additional booster fan (Figure 2). The air from the main duct would return to it after filtration or disinfection. The air purifier can be designed for full system flow rate (option 1) or partial (option 2). In this way some of the air flowing through the duct will be cleaned, as a result of which the number of pathogens in the air in the main duct will be reduced.

As an alternative to air filtration in the installation, and in addition to all other recommendations above, room air treatment with high-efficiency air purifiers (e.g., HEPA or electrostatic filters) or pathogen inactivation by air ionization (Figure 1 location E).

RESULTS

Influence of air filter location on recirculation of pollutants

When locating air filters one should also take into account possible paths of unfavorable air flows in the ventilation system, such as mutual location of the air intake and the air discharge and possible partial return of air between these elements (in [20] out of 13 analyzed cases, this type of leakage was found in 5 of them from 4% to 100%), leaks in the heat recovery system with unfavorable location of fans – these problems are described in more details in [3a, 3c, 17]. These aspects should also be taken into account when choosing the type and method of filtration and determining its effectiveness. With the source of contaminants in the room, the amount of contaminants returned to the room with the supply air depends on the type of filter, the possibility of leakage in the heat recovery system, and the proportion of exhaust air in the intake air.

Figure 3 presents a diagram of an air handling unit with a rotary heat recovery exchanger, which in accordance with the regulations [14], may have a leakage of up to 5% with pressure difference 400 Pa). The direction and leakage rate of the air handling unit heat recovery system is related to the configuration of the fans (Figure 4). With unfavorable fan configuration the extracted air from the room can get to the supply air through leaks in the heat recovery system (configuration ”b”, in some conditions “a” and very rare “d”), and outdoor air can get to exhaust air (configuration “c”, in some conditions in “d” and “a”). According to the REHVA guidelines [17], in the case of unfavorable fan configurations, the share of extract air in the supply air can reach up to 20% for configuration “a” and 25% for configuration “b”, and the share of returned outdoor air in exhausted air can reach up to 15% for configuration “a”, 30% for configuration “d” and 50% for configuration “c”.

Additional filters in the system can be located (Figure 3) on the supply air after the second filtration stage or instead of it. In case of placing the filter on the extract air it can be located before or after the existing filter depending on the type of filter used – for example if it would be an absolute filter (with higher accuracy) it would be located after the existing filter (gradation of capturing contaminants).

Table 2 shows the results of the calculations of the effect of filter location and fan configuration of the air handling unit with heat recovery on returning contaminants from the extracted air to the supply and exhaust air. For the following assumptions, it is shown what percentage of the pollutants extracted from the room will be in the supply air, in air exhausted to the outdoors, and in outdoor air intake:

- The source of the contamination is located in a ventilated room.

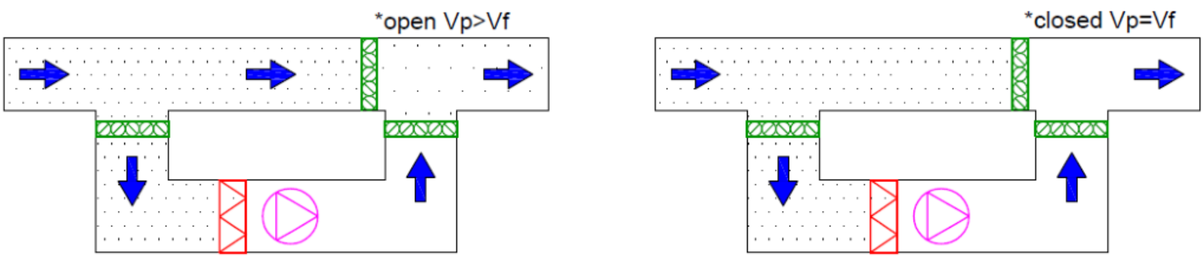

Figure 2. The idea of a cleaning device in the by-pass duct, based on [3a]
* – additional damper Vp – installation air flow, Vf – filter air flow

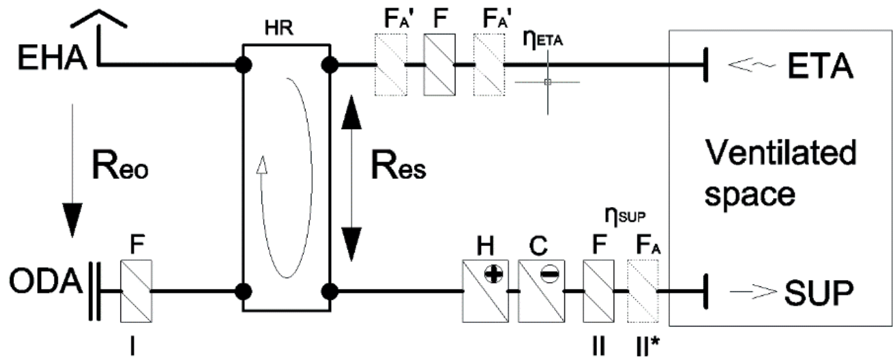

Figure 3. Diagram of the ventilation device and the locations of additional air purification facilities under consideration, FA – additional filter on the supply air, FA’ – additional filter on the extract air, Res – air flow of leak between extract and supply air and ventilating air flow ratio, Reo – air flow of leak between air intake and air discharge and ventilating air flow, EHA – exhaust air, ETA – extract air, ODA – outdoor air, SUP – supply air, ηSUP – efficiency of the additional filter on the supply air, ηETA – efficiency of the additional filter on the extract air

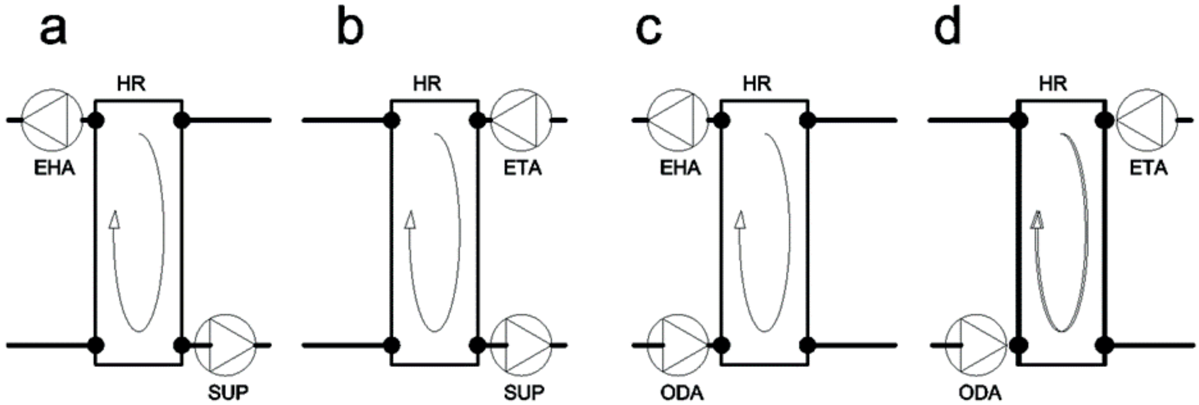

Figure 4. Possible configurations of the fans in relation to the heat recovery system in the air handling unit

- There is a leak in the heat recovery section R_{es} and its rate and direction depend on the configuration of the air handling unit fans.
- Assumed filtration efficiency of analyzed pollutant for location of additional filter on exhaust η_{ETA} and supply η_{SUP} equals 95%,
- A constant supply and extract air flow rate and a unidirectional leakage in the heat recovery system are assumed. For configuration only unfavorable direction of the leakage was considered.

Based on the results of the calculations presented in Table 2, it can be seen that:

- The location of the filter and pressure distribution in air handling unit affects the presence and concentration of contaminants in different parts of the system.
- The amount of contaminants returned increases with the leakage rate.
- Unfavorable positioning of the air intake relative to the air discharge increases amount of contaminants in supply air.
- The same filter locations in the air handling unit for different fan configurations results in different amounts of contamination in different parts of the system.
- The highest percentage of contaminants returned to the supply air can occur in the case of configuration “b” 25.0%, and in the case of unfavorably located intake relative to the discharge 30.6%.
- In the case of configuration “a” recommended by [17] and most commonly observed among manufacturers of air handling units, with unfavorable pressure system, these values are also high and are 20.0% and 26.4% respectively.
- The use of additional filters on both the supply and exhaust air significantly reduces the amount of contaminants returned even in the

Table 2. Filtration efficiency for different filter location and fan configuration in the air handling unit

Fans configuration	η_{ETA}, %	η_{SUP}, %	R_{eo}, %	R_{es}, %	Recirculated part of contaminants, CR			
					EHA, %	ODA, %	ETA, %	SUP, %
a i b	0	0	0	5	95.00	0.00	100	5.00
a i b	0	0	10	5	95.00	9.50	100	14.03
a	0	0	0	20	80.00	0.00	100	20.00
a	0	0	10	20	80.00	8.00	100	26.40
a i b	95	0	0	5	4.75	0.00	100	0.25
a i b	95	0	10	5	4.75	0.50	100	0.73
a	95	0	0	20	4.00	0.00	100	1.00
a	95	0	10	20	4.00	0.50	100	1.40
a i b	0	95	0	5	95.00	0.00	100	0.25
a i b	0	95	10	5	95.00	9.50	100	0.70
a	0	95	0	20	80.00	0.00	100	1.00
a	0	95	10	20	80.00	8.00	100	1.32
a i b	95	95	0	5	4.75	0.00	100	0.01
a i b	95	95	10	5	4.75	0.48	100	0.04
a	95	95	0	20	4.00	0.00	100	0.05
a	95	95	10	20	4.00	0.40	100	0.07
b	0	0	0	25	75.00	0.00	100	25.00
b	0	0	10	25	75.00	7.50	100	30.63
b	0	95	0	25	75.00	0.00	100	1.25
b	0	95	10	25	75.00	7.50	100	1.53
b	95	0	0	25	3.75	0.00	100	1.25
b	95	0	10	25	3.75	0.38	100	1.53
b	95	95	0	25	3.75	0.00	100	0.06
b	95	95	10	25	3.75	0.38	100	0.08
c i d	0	0	0	-5	95.24	0.00	100	0.00
c i d	0	0	10	-5	95.28	0.95	100	0.95
c	0	0	0	-50	66.67	0.00	100	0.00
c	0	0	10	-50	68.96	6.90	100	6.90
c i d	95	0	0	-5	4.76	0.00	100	0.00
c i d	95	0	10	-5	4.78	0.48	100	0.48
c	95	0	0	-50	3.33	0.00	100	0.00
c	95	0	10	-50	3.45	0.34	100	0.34
c i d	0	95	0	-5	95.24	0.00	100	0.00
c i d	0	95	10	-5	95.69	9.57	100	9.57
c	0	95	0	-50	66.67	0.00	100	0.00
c	0	95	10	-50	68.96	6.90	100	6.90
c i d	95	95	0	-5	4.76	0.00	100	0.00
c i d	95	95	10	-5	4.78	0.48	100	0.02
c	95	95	0	-50	3.33	0.00	100	0.00
c	95	95	10	-50	3.45	0.34	100	0.02
d	95	0	0	-30	3.85	0.00	100	0.00
d	95	0	10	-30	3.94	0.39	100	0.39
d	0	95	0	-30	76.92	0.00	100	0.00
d	0	95	10	-30	78.74	7.87	100	7.87
d	95	95	0	-30	3.85	0.00	100	0.00
d	95	95	10	-30	3.93	0.39	100	0.39

Note: η_{ETA} – efficiency of the additional filter on the extract air, η_{SUP} – efficiency of the additional filter on the supply air, R_{eo} – air flow between air intake and air discharge and ventilating air flow ratio, R_{es} – air flow of leak between extract and supply air and ventilating air flow ratio, EHA – exhaust air, ODA – outdoor air, ETA – extract air, SUP – supply air, CR – contaminant recirculation ratio

case of unfavorable fan configurations, air handling unit pressure distribution and suction of contaminated exhaust air to the air intake.
- The greatest effect can be achieved by using additional filters on the supply and exhaust simultaneously.
- Placing additional filters on the exhaust reduces the amount of contaminants in the air being exhausted to the outside, which for some types of contaminants may not be insignificant.

Influence of additional air pressure drops on the selection of air handling units

Since the replacement of a filter with a more efficient HEPA filter is associated with a significant increase of pressure drop. Therefore the fans in the air handling unit should be able to increase the compression by a reasonable value with designed air flow V_p (Figure 5). Therefore authors recommend to select fans for lower rotational speed, depending on the case for example about 70% of the nominal rotational speed (Figure 5). A centrifugal fan selected in such a manner, usually, operates in these conditions at maximum efficiency (η_c) of the electric motor, i.e. favorably from the point of view of the energy performance of the building. The reserve (Δp_F) makes it possible to replace the filter with a more efficient one, but with a higher pressure drop. Although the investment costs increase, it is possible to change the filtration efficiency. In addition, the ventilation unit designed this way works quieter. When selecting a fan, the Specific Fan Power (SFP) may be a limitation, whose permissible value for fans in ventilation and air-conditioning systems is specified in the regulations [14].

Authors also recommend to use fans with bearings that allow the speed to be increased above the nominal value and to operate at a current frequency higher than 50 Hz.

Principles of new ventilation designing

Based on analysis results, authors proposed the principles for designing of new ventilation and air conditioning systems in buildings that are not health care facilities. When designing air handling units with a configuration that prevents the return of contaminants – save pressure differences and the filters that provide the best possible air purification considering the fan's capabilities should be chosen. The devices cleaning efficiency should be considered in combination with the pressure distribution in the air handling unit. Fans ought to be selected with a reserve (e.g. at 70% speed) with the highest efficiency, ensuring a pressure reserve for more efficient filter replacement. Providing additional sections in the air handling unit to enable the addition or replacement of more efficient filters is suggested. When locating the units (e.g. in the machine room) make sure there is enough space to mount bypass filters or to install UVc lamps – adequate installation length sections. Air handling units with combined intake and discharge are not recommended. For reasons of mechanical stress, it is not advisable to design a system in which the heat exchanger is located in

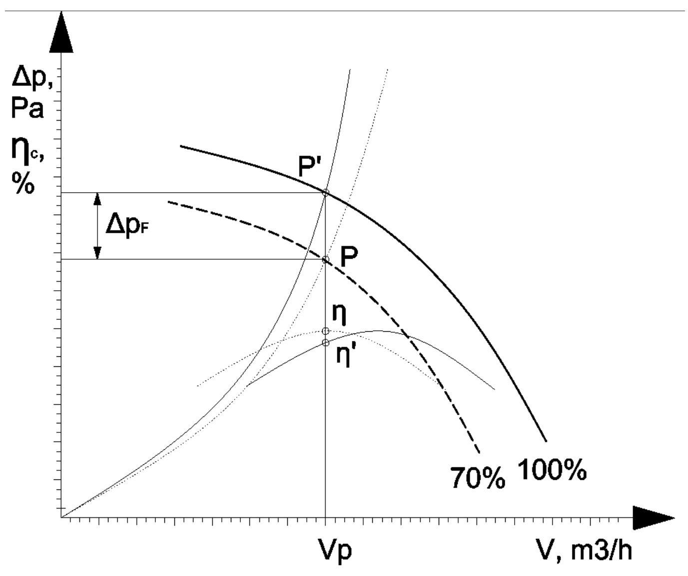

Figure 5.. Change of fan operation state after increasing of filters pressure drop

the suction section of one fan and in the discharge section of the second fan. The resulting high pressure differential could, over time, damage and unseal the system.

Configuration ”a” and “b” of air handling units, with properly provided pressure distribution and located filters, appear to be the most advantageous in terms of reducing the return of contaminants at their source in the room.

CONCLUSIONS

The current global situation challenges scientists and engineers to be multi-dimensional in their approach to design issues and to find and identify the best solutions, and it is necessary to implement as soon as possible effective measures in existing HVAC systems and to create new standards for the design of HVAC systems secured in the event of a threat similar to that of today or providing the possibility of rapid adaptation to such conditions.

Assuming that the ventilation system can potentially spread contamination or pathogens, it becomes necessary to prevent this effect. Modern ventilation systems should be possibly “resistant” to such situations and give the opportunity to respond appropriately when a new threat arises.

New modified design standards must also take into account the risks highlighted by the pandemic while respecting current trends in energy and energy conservation and ensuring appropriate microclimate conditions.

Therefore, it is worthwhile, designing all new ventilation systems, already today to pay attention to the possible occurrence of potential hazards of this type in the future and so design the organization of air exchange systems, the location of ducts, air purification capabilities, locations of air intakes and discharge and configurations of air handling units, to reduce as much as possible the negative effects of the possible operation of the system in the adverse conditions that the world has encountered today and may encounter in the future again.

During the COVID-19 pandemic, there were many recommendations in the literature indicating emergency measures to improve the functioning of ventilation systems to the risk of airborne transmission of the pathogen. However, there is a need to develop new standards for the design of these systems in accordance with new paradigms.

Therefore, in the article benefits and problems resulting from possible locations of air filtration or sterilization elements in the ventilation system was discussed and solutions giving the possibility of fast modification according to the appearing danger was proposed by indicating recommended solutions for future design in which the risk of leaks in ventilation systems is minimized, there is a reserve on the fan and a reserve of space to allow modification if necessary by, for example, the use of additional filtration or bypasses.

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