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Respiratory infection risk based ventilation and room conditioning design method with year-round thermal comfort control in modern office buildings

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Abstract. The new decade will be a major challenge for built environment to satisfy building users and owners demands for superior IEQ in the work environment and tackle infection risk issues brought by SARS-CoV-2 pandemic. We collected thermal comfort and IAQ data from modern Estonian office buildings showing that improvements are needed in whole chain of the HVAC science, engineering and manufacturing because current solutions in these buildings have led to many complaints of draught and readjustments of supply air temperature have typically compromised energy performance. To achieve Category II or I IEQ, more systematic design methodologies are needed. Additionally, ventilation rate and air distribution dimensioning based on respiratory infection risk has to be taken into use as a complementary method of existing ones for office space AC and ventilation design, where both net floor area and occupant number define the required ventilation. Based on air velocity and temperature (operative, supply air and local) measurements conducted in five office buildings a new IEQ design methods were developed to satisfy the thermal comfort indices leading to low occupant complaints and not compromising energy performance at the same time. In well ventilated Category I and II office spaces, control of draught risk is an extensive design task for which new methodology was developed. Our method focuses separately on IEQ parameters during heating, cooling and midseason, from which the latter one is the longest and the most dominating one. The design method is presented by connecting thermal comfort and infection risk with ventilation rate. Infection risk based air flow rate selection diagram and corresponding air velocity diagrams for an open plan office and 3-person room showing the possibilities to size ventilation for the event reproduction number of R = 0.5 were constructed.

1 Introduction

Next to thermal comfort, a suggestion for new criterion has risen in the matter of airborne respiratory contagions. COVID-19 has clearly proved the need for year-round infection risk control. A new design method was proposed to be used for designing rooms with low infection risk [1]. Buildings must provide infection risk safety throughout the year, regardless of the weather and season. Therefore, dimensioning and analysing HVAC systems compliance with infection risk criterion, cooling, midseason and heating thermal comfort guidelines must be followed.

In a study [2] conducted in Tallinn, thermal comfort (TC) and draught rate (*DR*) assessment was carried out in both heating and cooling period conditions. The office buildings were equipped with different HVAC solutions. The need of careful air distribution design in order to meet comfort requirements in open-plan office layouts was emphasized. The occupant complaints for TC and *DR* were stressed throughout the year. The study highlighted, that during heating period, ventilation supply air temperature (t_{sup}) was gradually stepped up to reduce occupant complaints regarding draught due to higher indoor air temperature (t_i) than recommended.

Midseason period may become underestimated from the point of view of the functioning of the building, while concentrating on the peaks of the heating or cooling. EN 16798-1 [3] defines the midseason with ambient temperature between 10-15°C. In EVS-EN 16798-1 Estonian national annex [4], the heating season is described as <12°C and cooling season as >17°C. On the basis of outdoor running mean temperature equation [3] and weather data [5] in Tallinn between 2011-2020, length of these three periods vary. On the first case, the average cooling period constitutes 19%, midseason 20% and heating 61% of the working hours. On the second, national annex case, same proportions are 11%, 23% and 66%. Heating period is the longest, but it is typical that majority of space heating energy is consumed outside working hours [6]. Hence, the majority of occupied hours, office building rooms are in a light need of heating or cooling energy, both or none. Worth noting, that according to 16798-2 [7], 6% (126 h) annually, 25% (44 h) monthly and 50% (20 h) weekly of the occupied hours are allowed to deviate from the indoor climate criteria. In addition, oversized HVAC

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systems meeting indoor climate category 100% of the time often result in high space demand requirements and will annually operate less efficiently.

A simplified function about temperature difference between indoor air temperature and supply air temperature ($t_{i\text{-}sup}$) and local mean air velocity (v_a) is not available. Although, $t_{i\text{-}sup}$ relation to ventilation effectiveness is described in CR 1752 [8] ventilation effectiveness in general is well presented in Rehva Guidebook and in a review made by Cao et al. [9]. Optimum operative temperature (t_{op}) as a function of clothing and activity, with turbulence (*Tu*) by *DR* and recommended t_i range is provided in ISO 7730 [10].

The goal of this paper is to meet both thermal comfort [3], [10] and infection risk control [1] criterion at the same time. A simplified selection tool based [11] case study with a smaller, 3-person and with an open plan office with 7 person, is conducted by following the guidelines of chilled beam design [12], [13].

2 Methods

Comparing simultaneously t_i and v_a criterion [4], we coloured (Figure 1) the areas on the background on the graph of maximum allowable mean air velocity as function of indoor air temperature [10].

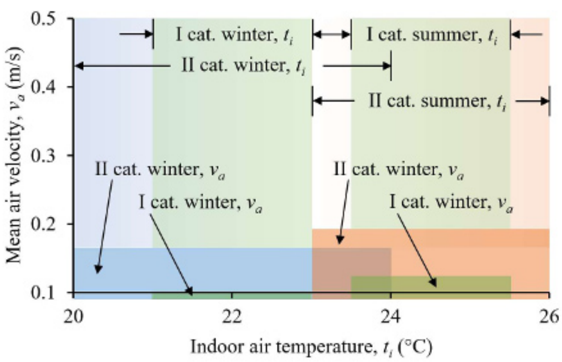
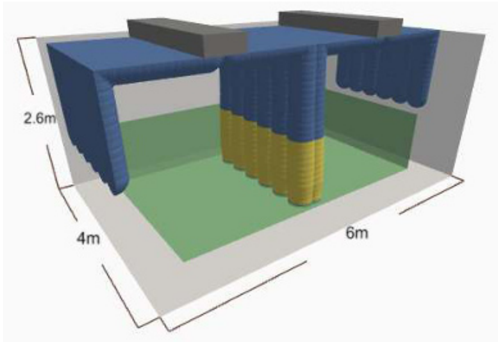


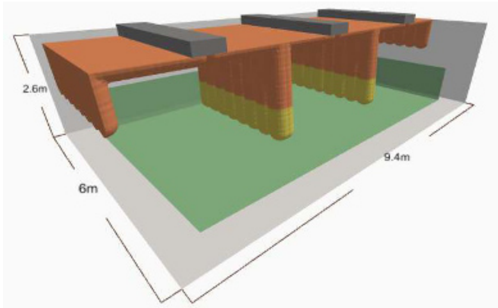
Figure 1. Maximum allowable mean air velocity as function of indoor air temperature. [3], [10]

Figure 1 coloured underlay is used in the results section for Figure 4. To approach with a simplified all weather and season inclusive method, t_i values between 20 to 26 °C are used in case study room calculations (Table 1). There are not much HVAC selection tools including comprehensive option range available for room conditioning, ventilation and heating design concurrently. Therefore, a 4-pipe chilled beam selection process is suitable for this paper to assess the performance of thermal comfort and draught risk simultaneously. Therefore, FläktGroup web-based selection tool [11] is suitable for this process and used in this paper. However, chosen platform is still unable to compare HVAC combinations directly, investigated in office building study conducted in Tallinn [2].

In Figure 2, room visualizations for cooling and heating mode from the selection tool are provided. Room parameters are presented in Table 1. Occupied zone in this study is 0.6 m from walls and v_a is compared on the height of 1.1 m.



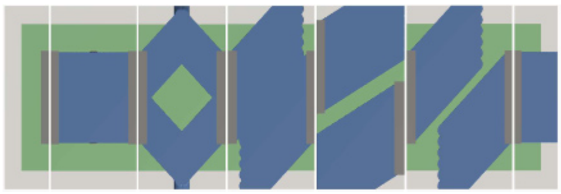
(a)



(b)

Figure 2. 3-person office (a) and open plan office (b) visualization for heating mode with web-based selection tool. [11]

Following the goal of this paper to avoid draught in all cases, methods for managing airflows is presented in the Figure 3. Using flow pattern control and changing the position of the beams for higher Q_v values, thermal comfort is not affected in the lower ventilation rates.



(1) (2) (3) (4) (5) (6) (7)

Figure 3. Illustration of chilled beam flow pattern control [11]. Blade settings: (1) no airflow, (2) 0° angle, (3) 45° angle symmetrical, (4) 45° angle opposing, (5) 30° angle opposing and cross-centre line detached, (6) 45° angle opposing and centre line detached, (7) 0°C angle airflow to wall.

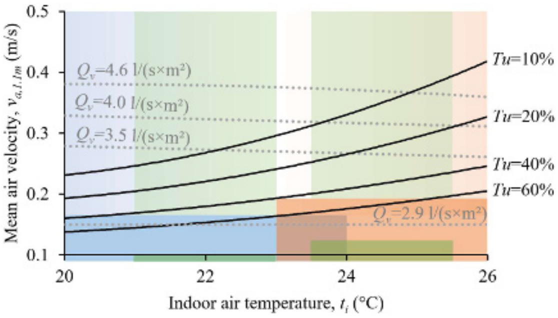
Case study room parameters and HVAC system are described in Table 1. In the value cell, recommended design values are provided in brackets [12]. We analysed Q_v values from 0.5 to 4.5 l/(s×m²) with the step of 0.5. The values vary slightly due to the input precision in the tool [11]. Nominal Q_v values for regular schedule are calculated by the components of occupants and building emission by the floor area (*A*) [3]. The probability of infection risk is determined according to the new design method proposed, using ventilation rate at a given quanta emission rate and probability of infection [1].

Table 1. Case study rooms, indoor climate and room unit description.

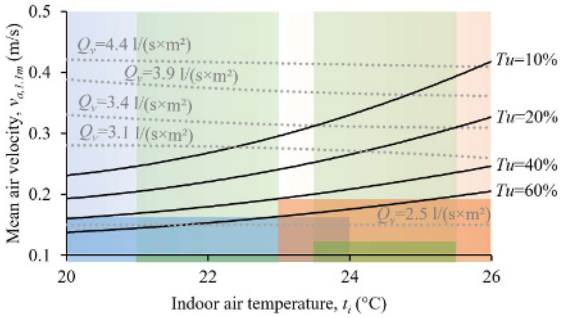
Room parameters	
3-person office $N = 3$, $D = 8$ h $Q_b = 10$ quanta/h	$A = 24$ m², $h = 2.6$m $V = 62.4$ m³ $Q_v = \pm 38$ l/s
Open plan office $N = 7$, $D = 8$ h $Q_b = 10$ quanta/h	$A = 56$ m², $h = 2.6$m $V = 146.6$ m³ $Q_v = \pm 88$ l/s
System	
Air pressure drop	100 Pa (30…120 Pa)
Supply air temp cooling/heating	19/20 °C (18…20/19…21 °C)
Inlet water temperature cooling/heating	18/40°C (14…18/30…45°C)
Inlet water flow cooling/heating	0.03/0.03 l/s (0.03…0.10/0.03…0.10 l/s)
Ceiling temperature	+1 °C
Room temperature cooling/heating	20,22,24,26/20.5,21,21.5,22 °C (24.5±1.5/22±1.5 °C)
Power cooling/heating	13…101/30…48 W/m² [60…80(<120)/25…35(<50) W/m²]
v_a cooling/heating	<0.15…/<0.15… m/s [0.18(0.23)/0.15(0.18) m/s]
Room units	
4-pipe chilled beam FläktGroup iQ STAR WEGA II	2×240 cm (3-person office) 3×300 cm (open plan office) X-Flow (connection 160 mm) PI funtion with flow pattern angle control

3 Results and discussion

Using Figure 1 as an underlay, we constructed Figure 4 to illustrate the results of the 3-person office and the open plan office case scenarios for cooling. In the smaller office, $v_a < 0.15$ m/s was reached up to $Q_v = 3.0$ l/(s×m²). In the open plan office, v_a limit was achievable up to $Q_v = 2.5$ l/(s×m²). Higher values of Q_v with recommended v_a can be reached in both rooms and in both cooling and heating cases by rotating flow pattern control blades and increasing the distance between chilled beams centre or cross-centre lines (see Figure 3).



(a)



(b)

Figure 4. 3-person office (a) and open plan office (b) ventilation rate case scenarios for cooling in compliance with II category draught rate (*DR*=20%) with maximum allowable mean air velocity as function of indoor air temperature and turbulence intensity. [3], [10]

Based on the simplified Q_v equation [1], description from Table 1, results of Figure 4 with eliminated higher than limit v_a values, event reproduction number and probability of infection for susceptibles is presented in Figure 5 below as function of Q_v. Open plan office and 3-person office rooms are displayed as one function on both CRE ε=1.0 and 0.8 cases as for cooling and heating assuming worse effectiveness for the latter. The difference between cooling and heating decreases with the increase of Q_v values. To achieve $R = 0.5$ in an open plan office, about 3.0 l/(s×m²) would be needed. In 3-person office, smaller airflow rate would be enough, but to limit the individual probability of infection to $p = 0.1$, about 4.0 l/(s×m²) would be needed.

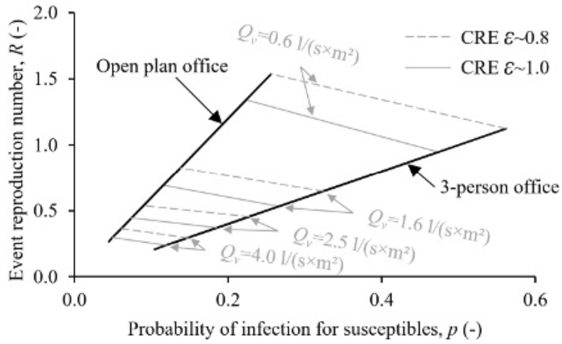


Figure 5. Event reproduction number and probability of infection for susceptibles in 3-person office and open plan office.

Figure 4 and Figure 5 share the calculated case lines of room Q_v values. Infection risk selections must be planned independently from seasonality. Therefore, thermal comfort indices are taken into account through parameters affecting CRE ε. However, to evaluate ventilation effectiveness more deeply, CFD simulations or tracer gas measurement experiments would be needed. Figure 4 could be further developed to connect cooling and heating loads with building façade parameters such as window-to-wall ratio and glass solar factor including orientations. This is important, as façade parameters affect dimensioning of HVAC systems at a large scale.

Although some HVAC systems should create the prerequisites for ensuring more comfort, the single best solution is not easy to determine. Number of parameters must be taken into account when designing a HVAC solution. Pressure on budget and efficiently maximized space utilization refer to different combinations being used more often instead of separate systems and components. 4-pipe open or suspended ceiling chilled beams may become replaced easily in case of low air exchange or high cooling loads. The choice of chilled beams for cooling may not be suitable and fan-coil units become an option. In the case heating, convectors can meet the required power more easily or underfloor heating may be required by the client. However, in the office building thermal comfort study in Tallinn, fan-coil units showed the worst results, as expected. Using fan-coil units for cooling will likely reduce the useful floor area for workspace. Using fan-coil units the contribution to the respiratory infection risk must be excluded. Nonetheless, using fan-coils or chilled beams for heating, selection principles must be followed carefully.

As the study of infection risk calculation method [1] did not provide a rule of thumb, different room type and size need separate analysis. Meeting infection risk parameters, dimensioning ventilation rates in the early phase of the projects will conclude in tendencies to oversizing ventilation ducts. The latter supports the designing method for final pressure drop. However, following the energy efficiency principles, need for variable air volume flow systems may emerge. Therefore, the mode of infection risk in addition to t_i, CO_2 or presence, must be added to the VAV system control. Hence, VAV based chilled beam product was used in this study. Significant difference of infection risk approach compared to conventional design on VAV systems is expressed in nominal airflow description. Ventilation system is sized on the maximum occupant number and in other times, air change rate is decreased by lower presence. In the case of infection risk control, ventilation system must be sized to lower the probability of infection. Therefore, the conventionally sized ventilation rate moves down between the minimum and maximum airflow. From the viewpoint of non-viral situation, higher cooling and heating power becomes available with the oversized VAV system. Although, the number of persons will become more limited in the viral situation for higher occupancy density office landscapes.

In this paper, with the methodological approach described, there are many limitations to consider. To begin with, local thermal comfort components – vertical t_i difference, range of floor surface temperature and radiant temperature asymmetry are not discussed in this paper. The impact of these factors are described and stressed in Rehva Guidebooks [12], [13] as well as the internal heat gains and human movement or activities. The aspects of low *RH* levels during heating period should be reconsidered. In the office building study [2] in Estonia higher heating period t_i values were recorded, therefore lower *RH* levels occur. If virus situation mode is switched on for ventilation, including higher ventilation rates, *RH* level is also affected. Aspects of the virus spread related to *RH* levels is another thing to consider. The dependence of the ventilation, cooling and heating loads W/m² and acoustics is not covered in this paper and should be studied. In the calculations performed, the noise level remained below 35 dB(A).

Secondly, the budget issues, starting with higher number and larger room units, higher space need for technical shafts and rooms, oversized heating and cooling coils and ventilators in air handling units with oversized heating and cooling plants. HVAC automation system differences needed are also not covered in this paper. Natural and hybrid ventilation systems and solutions are left out of this paper's approach, as these would be unique for new buildings in Estonia. The limited usage time would apply both during heating period and also at the time of cooling period referring to buildings equipped with condensate free mechanical cooling systems. The proposed selection method becomes more complex the larger the room area or the non-standard the shape of the room, including multi and connected zones. In addition, concepts of pulsating, protected occupied zone, personal ventilation solutions among others should be studied in depth. In conclusion, a wider discussion regarding infection risk control is needed to determine:

- How to include adequate infection risk related information on ventilation or combined HVAC room unit selection tools and also in the design;
- Whether the same indoor climate criteria apply to indoor climate classes in a viral situation;
- Advisability of wider use of variable air volume flow systems;
- How to deal with existing buildings, where there is not enough room for larger ventilation systems or occupant numbers must be limited in a viral situation.

4 Conclusions

Design of ventilation systems for the threshold of respiratory infection risk control is challenging. Planning, dimensioning and selection of spatial solutions is no longer static, but becomes a complex choice, taking into account many different aspects at the same time. Therefore, ventilation manufacturers, designers and builders, who are able to implement better solutions through more scenarios during planning process, flexibility and sustainability during usage period, may have a greater advantage. In buildings with proper structures and well-thought-out façade solutions, the boundaries between heating and cooling periods become less clear and the need for heating and cooling more simultaneous. Therefore, a year-round approach for ventilation and room conditioning TC and respiratory infection risk control was proposed in this paper. Using a web-based selection tool, 4-pipe chilled beam solution with a flow pattern and VAV control was tested and adjusted to the settings to meet both criteria. We constructed the infection risk based air flow rate selection diagram and corresponding air velocity diagrams for an open plan office and 3-person room showing the possibilities to size ventilation for the event reproduction number of $R = 0.5$.

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Abbreviations, terms and symbols

A	floor area of the room (m²)
CRE ε	contaminant removal effectiveness (-)
D	duration of the occupancy (h)
DR	draught rate (%)
h	room height (m)
HVAC	heating, ventilation and air conditioning
N	total number of persons in the room
p	probability of infection for susceptibles (-)
Q_b	volumetric breathing rate of an occup. (m³/h)
Q_v	ventilation airflow rate (l/s)
R	event production number (-)
TC	thermal comfort
t_i	indoor air temperature (°C)
t_o	operative temperature (°C)
t_{sup}	supply air temperature (°C)
V	volume of the room (m³)
v_a	mean air velocity (m/s)
VAV	variable air volume

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