Analysis of Educational Building’s Ventilation Suitability to Prevent the Spread of Coronavirus (SARS-CoV-2)

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In a larger educational building in Slovenia, we examined the efficiency of ventilation systems by analysing the operation of the heating, ventilation, and air conditioning (HVAC) system in several classrooms. Using the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) COVID-19 ventilation calculator, the probability of infection due to the spread of coronavirus through aerosol particles and the reproduction number were calculated based on the classroom occupancy, ventilation rates, and other parameters (i.e., classroom characteristics, preventive measures). Firstly, different levels of ventilation capacity (50 % and 80 %) were applied. Considering the distance between occupants 1.5 m and wearing the masks of all participants, the probability of infection during lectures was always lower than 1 %. Secondly, the maximum number of students that can attend lectures is about 30 %, as calculated according to the legal requirements, recommendations, and given conditions.

Keywords: classroom ventilation, REHVA calculator, probability of infection, reproduction number, HVAC system

O INTRODUCTION

It is well known how important the design of heating, ventilation, air conditioning (HVAC) systems is to achieve adequate air quality, while not deteriorating thermal comfort [1]. Since the Coronavirus disease COVID-19 outbreak, preventive measures have been taken to mitigate transmission risks (i.e., airborne, contacts) in buildings. Ventilation solutions present the main engineering controls described in the traditional infection control hierarchy [2] to reduce environmental risks of airborne transmission [3] to [5].

Expelled respiratory droplets that are airborne range from less than 1 µm to more than 100 µm in diameter. Airborne transmission depends on the droplet size and includes i) short-range region for close contact (i.e., large droplets up to 2 mm that fall within 1.5 m) and ii) long-range region (i.e., small droplets less than 50 µm fall beyond 1.5 m distance) [6] and [7]. In indoor air, coronavirus SARS-CoV-2 can remain active for up to 3 hours and up to 2 to 3 days on room surfaces in common indoor conditions [8]. Therefore, the main role of efficient ventilation is to ensure a sufficient amount of fresh air per occupant while simultaneously removing the harmful airborne microbes. A study by Nishiura et al. [9] highlighted that the odds that a primary case transmitted COVID-19 in a closed environment was 18.7 times greater compared to an open-air environment.

Poorly designed and/or not properly maintained HVAC systems enable the airborne droplets to be easily transported around the spaces in buildings, and therefore, such a method of transmission is becoming increasingly important [10] and [11].

Quite a few studies have been done analysing HVAC systems and the impact of natural ventilation (opening of windows) [4], [12] and [13]. It was found that with appropriate measures regarding ventilation, the probability of infection is relatively low (less than 1 %) [14].

Similarly, our study aimed to verify the ventilation efficiency in the selected educational building in Slovenia and to calculate the transmission risks for COVID-19. The main question was whether the existing ventilation system meets the requirements of standards to prevent the spread of SARS-CoV-2...
during normal occupancy of classrooms and how the probability of infection could be quantified.

1 METHODS

To be able to assess the current state of the probability of infection in the selected building and to be able to propose appropriate measures, the REHVA COVID-19 ventilation calculator was used [15]. The calculation is based on the Wells-Riley model [16], which determines the probability of infection for the selected space and human activity. The probability of infection \( p \) is defined by Eq (1):

\[
p = 1 - e^{-n},
\]

where \( n \) is the number of quanta inhaled.

Quantum represents the number of airborne droplet nuclei that cause infection in 63 % of susceptible individuals. This depends on the origin of the viruses, which is defined with quanta emission rate, \( E \), [quanta/h]. The quanta inhaled \( (n, \text{ quanta}) \) depends on the time-average quanta concentration, \( C_{\text{avg}} \), [quanta/m³], the volumetric breathing rate of an occupant, \( Q_b \), [m³/h] and the duration of the occupancy, \( t \), [h] as shown in Eq. (2):

\[
n = C_{\text{avg}} Q_b t.
\]

\( C_{\text{avg}} \) is defined in Eq. (3), where \( V \) represents the volume of the room [m³], \( \lambda \) is a first-order loss rate coefficient for quanta/h due to the summed effects of ventilation, deposition onto surfaces and virus decay. Values for \( \lambda \) are taken from studies [17] to [19]. Estimated values for \( E \) and \( Q_b \) are based on the studies of the Skagit Valley Chorale event [5] and quanta generation rates for SARS-CoV-2 [6] and are given in Table 1.

\[
C_{\text{avg}} = \frac{E}{\lambda V} \left[ 1 - \frac{1}{\lambda t} \left( e^{-\lambda t} - 1 \right) \right].
\]

<table>
<thead>
<tr>
<th>Human activity</th>
<th>Quanta emission rate, ( E ), [quanta/h/occupant]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting, oral breathing</td>
<td>0.72</td>
</tr>
<tr>
<td>Heavy activity, oral breathing</td>
<td>4.9</td>
</tr>
<tr>
<td>Light activity, speaking</td>
<td>9.7</td>
</tr>
<tr>
<td>Light activity, singing (or loudly speaking)</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 1. 66th percentile SARS-CoV-2 quanta emission rates for different activities [20]

In addition to the calculation of the probability of infection, it was also necessary to define its acceptable value. For this, several studies propose to define the event reproduction number \( R \). It is defined as the number of new disease cases divided by the number of infectors and its value should be below 0.1 [15].

<table>
<thead>
<tr>
<th>Human activity</th>
<th>Breathing rate, ( Q_b ), [m³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing (office, classroom)</td>
<td>0.54</td>
</tr>
<tr>
<td>Talking (meeting room, restaurant)</td>
<td>1.10</td>
</tr>
<tr>
<td>Light exercise (shopping)</td>
<td>1.38</td>
</tr>
<tr>
<td>Heavy exercise (sports)</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Table 2. Volumetric breathing rates [21] and [22]

Mentioned should also be the assumptions made in this model. It is assumed that quanta are emitted at a constant rate throughout the event; the infected occupant is present in the room throughout all occupancy time; an infectious respiratory aerosol is evenly distributed throughout the well-mixed room air; infectious quanta are removed by ventilation, filtration, deposition, and airborne virus decay.

2 EXPERIMENTAL AND CALCULATIONS

2.1 Experimental

An inspection of ventilation systems with a description of mechanical installations of the selected educational building was made as part of the energy audit in 2012. Mechanical installation systems have not changed much since then, as only service and maintenance works have been carried out in the meantime. We also reviewed some parameters (type of recuperation, surface area, height and volume of the classrooms, air flow rate of air-conditioning (AC) unit, type of air inlet, the maximum number of occupants, number of seats, etc.) and measured them based on the obtained data. The results are given in Table 3. Validation of their Supervisory control and data acquisition (SCADA) system was performed using the reference measuring equipment Testo 400 (Universal IAQ instrument), according to the standard EN ISO 12599 requirements [23]. The cross-checking of temperature, \( CO_2 \) and air inlet velocity showed that their system deviates by less than 6 % from the reference. It should be noted that the \( CO_2 \) sensors from their SCADA system detect a higher value than the reference one, which in turn means that the ventilation turns on at lower \( CO_2 \) concentrations and consequently the ventilation is better. At the time of our measurement, the SCADA was set to increase power of the ventilation system at elevated \( CO_2 \) concentrations (>1000 ppm) in the air of classrooms.
The inspection followed the Methodology for Regular Inspections of Air-conditioning Systems [24].

6 AC units supplied air for 6 large classrooms (LCR) on the ground floor (LCR 1_G – LCR 6_G) and 1 AC unit for small classrooms (SCR) in the basement (SCR 1_B – SCR 6_B).

2.2 Calculations: the Probability of Infection and Reproduction Number

The following assumptions had to be made when calculating the probability of infection and the reproduction number using the REHVA COVID-19 ventilation calculator [15]:

- Proper wearing of the masks of all occupants was envisaged; the value for mask efficiency for susceptible occupant is 0.3, and the value for mask efficiency for the infectious occupant is 0.5.
- The virus decay was the default from the study by van Doremalen et al. [8], and its value is 0.63 h⁻¹.
- Deposition to surfaces was defaulted from the studies by Buonnano et al. [20] and Miller et al. [25], where the value could vary between 0.24 and 1.5 h⁻¹, depending on the aerosol particle size range. For the study, the value taken was 0.24 h⁻¹.
- Additional control measures (such as a removal rate of UV disinfection) were 0 h⁻¹.
- Quanta emission rate was 5 quanta/h.
- Breathing rate was 0.54 m³/h.
- Classroom occupancy was 12 h/day.
- The distance between the occupants is at least 1.5 m.
- There is only one infected occupant in the classroom.

3 RESULTS AND DISCUSSION

As presented in the previous chapter, we analysed the ventilation systems in the educational building and came to the following conclusions:

- All larger ventilation devices have rotary heat exchangers, which means that there is a possibility of the virus being transferred back into the classroom in the event of a leak.
- There is mixed-mode ventilation in large classrooms, which is not suitable for keeping the sufficient quality of air in the classroom. Small classrooms have a displacement mode of ventilation, which is more suitable from the air exchange point of view.
- The windows were opened after each lecture so that a large number of windows were completely opened for several minutes. Windows were also opened if the CO₂ sensor showed values above 1000 ppm.
- Ventilation ducts are not being cleaned.
- Large classrooms have ventilation efficiency controlled by CO₂ sensors, while small classrooms do not.

The results obtained from the computations are shown in Figs. 1 to 4 and Table 4. For LCR 1_G – LCR 6_G, the ventilation capacity was set at 50 % and 80 % (Figs. 1 and 2), and for SCR 1_B – SCR 6_B was assumed the ventilation with the same share of airflow (Figs. 3 and 4). Note: in some figures, the lines overlap.

As seen from Fig. 1, the probability of infection after 12 h is the highest in LCR 2_G, when it reaches 0.4 % with 50 % ventilation capacity. If ventilation capacity is increased to 80 %, the probability of infection is reduced to 0.27 %. This means a 28 % lower probability of infection. The lowest probability of infection is in LCR 6_G and LCR 5_G.

The same is true when comparing the reproduction number (Fig. 2). At 50 % ventilation capacity, the maximum value is 0.11 in LCR 2_G, and at 80 %, it is reduced to 0.07. The recommended value of the reproduction number is 0.5, and to control the epidemic, it should be kept below 1 [1].

### Table 3. Characteristics of AC units, classrooms and analysed ventilation scenarios

<table>
<thead>
<tr>
<th>Classroom</th>
<th>Air-conditioning unit</th>
<th>The airflow rate ([\text{m}^3/\text{h}])</th>
<th>Surface area of classroom ([\text{m}^2])</th>
<th>Classroom height ([\text{m}])</th>
<th>Max number of occupants (with 1.5 m distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCR 1_G</td>
<td>NP1: IMP KNMD 9/6 D25</td>
<td>4500</td>
<td>197</td>
<td>2.9</td>
<td>28</td>
</tr>
<tr>
<td>LCR 2_G</td>
<td>NP2: IMP KNMD 9/6 D25</td>
<td>4500</td>
<td>198</td>
<td>2.9</td>
<td>25</td>
</tr>
<tr>
<td>LCR 3_G</td>
<td>NP3: IMP KNMD 12/6 D25</td>
<td>5800</td>
<td>245</td>
<td>4.5</td>
<td>32</td>
</tr>
<tr>
<td>LCR 4_G</td>
<td>NP4: IMP KNMD 12/6 D25</td>
<td>5800</td>
<td>267</td>
<td>3.95</td>
<td>39</td>
</tr>
<tr>
<td>LCR 5_G</td>
<td>NP5: IMP KNMD 12/6 D25</td>
<td>9400</td>
<td>307</td>
<td>4.5</td>
<td>35</td>
</tr>
<tr>
<td>LCR 6_G</td>
<td>NP6: IMP KNMD 12/6 D25</td>
<td>9400</td>
<td>624</td>
<td>4.5</td>
<td>42</td>
</tr>
<tr>
<td>SCR 1_B – SCR 6_B</td>
<td>N1: IMP KNMD 9/9 D25</td>
<td>7505</td>
<td>509</td>
<td>2.9</td>
<td>73</td>
</tr>
</tbody>
</table>
It was envisaged that the fresh air is distributed equally among SCR 1_B – SCR 6_B. We can see that the probability of infection is still below 1.5 % (Fig. 3). The reproduction number is the highest in SCR 5_B (0.21 – Fig. 4), which is also the most problematic classroom because it has no windows. In Figs. 1 to 4, the values only consider the transmission of the virus by air in aerosols, i.e., assuming a distance of 1.5 m between occupants. Transmission with contact or droplets is not taken into account.

The evaluation of the adequacy of the value of ventilation was carried out with the legally required [24] and recommended values [26], where large classrooms (LCR 1_G – LCR 6_G) require 30 m\(^3\)/h air per occupant. 4 loads of classrooms were inspected (scenarios S1 – S4) according to the number of occupants present, which were determined for each classroom separately:

![Fig. 1. Probability of infection for the ground floor and the ventilation of a maximum value of; a) 50 %, and b) 80 %](image1)

![Fig. 2. Event reproduction number for the ground floor and the ventilation of a maximum value of; a) 50 %, and b) 80 %](image2)

![Fig. 3. Probability of infection for the basement and the ventilation of a maximum value of; a) 50 %, and b) 80 %](image3)
S1: Subject to all regulations and COVID-19 recommendations, safety distance between occupants 1.5 m.

S2: Half occupancy of classrooms.

S3: Maximum load after the epidemic (full occupancy of classrooms with occupants).

S4: Sufficient air volume (30 m$^3$/h/occupant), 1.5 m distance between occupants not considered.

Table 4. Set of scenarios on occupational load, airflow and AC capability

<table>
<thead>
<tr>
<th>Classroom</th>
<th>Number of seats [-]</th>
<th>AC capability at 100 % [m$^3$/h]</th>
<th>S1: Covid - needed airflow [m$^3$/h]</th>
<th>S2: 50 % occupancy - needed airflow [m$^3$/h]</th>
<th>S3: max occupancy - needed airflow [m$^3$/h]</th>
<th>S4: max number of occupants at 100 % capability [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCR 1_G</td>
<td>210</td>
<td>4500</td>
<td>840</td>
<td>3150</td>
<td>6300</td>
<td>150</td>
</tr>
<tr>
<td>LCR 2_G</td>
<td>196</td>
<td>4500</td>
<td>750</td>
<td>2940</td>
<td>5880</td>
<td>150</td>
</tr>
<tr>
<td>LCR 3_G</td>
<td>270</td>
<td>5800</td>
<td>960</td>
<td>4050</td>
<td>8100</td>
<td>193</td>
</tr>
<tr>
<td>LCR 4_G</td>
<td>330</td>
<td>5800</td>
<td>1170</td>
<td>4950</td>
<td>9900</td>
<td>193</td>
</tr>
<tr>
<td>LCR 5_G</td>
<td>304</td>
<td>9400</td>
<td>1050</td>
<td>4560</td>
<td>9120</td>
<td>313</td>
</tr>
<tr>
<td>LCR 6_G</td>
<td>200</td>
<td>9400</td>
<td>1260</td>
<td>6600</td>
<td>6600</td>
<td>313</td>
</tr>
<tr>
<td>SCR 1_B</td>
<td>63</td>
<td>1250</td>
<td>300</td>
<td>945</td>
<td>1890</td>
<td>41</td>
</tr>
<tr>
<td>SCR 2_B</td>
<td>56</td>
<td>1250</td>
<td>240</td>
<td>840</td>
<td>1680</td>
<td>41</td>
</tr>
<tr>
<td>SCR 3_B</td>
<td>56</td>
<td>1250</td>
<td>450</td>
<td>840</td>
<td>1680</td>
<td>41</td>
</tr>
<tr>
<td>SCR 4_B</td>
<td>42</td>
<td>1250</td>
<td>360</td>
<td>630</td>
<td>1260</td>
<td>41</td>
</tr>
<tr>
<td>SCR 5_B</td>
<td>70</td>
<td>1250</td>
<td>600</td>
<td>1050</td>
<td>2100</td>
<td>41</td>
</tr>
<tr>
<td>SCR 6_B</td>
<td>12</td>
<td>4500</td>
<td>180</td>
<td>180</td>
<td>360</td>
<td>41</td>
</tr>
</tbody>
</table>

S1: Subject to minimal required airflow and COVID-19 recommendations, safety distance between persons 1.5 m.

S2: Half occupancy of classrooms.

S3: Maximum load after the epidemic (full occupancy of classrooms with occupants).

S4: Sufficient air volume (30 m$^3$/h/person), 1.5 m distance between persons not taken into account.

Using the REHVA calculator, the probability of infection due to the spread of coronavirus through aerosol particles and the reproduction number for
each classroom at the selected educational building were calculated. Considering the distance between occupants 1.5 m and wearing the masks of all participants, the probability of infection was always lower than 1%. The acceptable reproduction number is less than 0.1 which was achieved in most of the cases. The most critical are cases with 50% capacity and when the occupancy time approaches 12 h. In reality, such a case is highly unlikely therefore spread of the virus should not be an issue.

In the calculations for the maximum allowed number of people in each classroom assuming all corona measures, i.e. 1.5 m distance and wearing the mask of all participants, about a third of the number of seats could be occupied.

The AC system was analysed also according to the required amount of fresh air to define how many people can be in individual classrooms with four specific scenarios (S1 to S4). It should be noted that scenarios S2, S3 and S4 are not appropriate during the COVID-19 situation and do not take into account the distance of 1.5 m, but the prescribed value of the fresh air is guaranteed according to the rules (ventilation rate of 30 m³/h/occupant). Due to the construction of the ventilation system at the educational building before 2002, when the Rules on ventilation and air conditioning of buildings [27] were amended, we concluded that the occupancy of large classrooms could be 70% if the ventilation system is operating at full power. In the case of full-day occupancy of large classrooms the ventilation system operating with at least 80% power is recommended. In the case of 80% ventilation capacity, a sufficient amount of fresh air is provided for the half occupancy of classrooms.

6 REFERENCES


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