Simulation of IAQ and thermal comfort of a classroom at various ventilation strategies

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Abstract. It has been reported that there is a large issue regarding the IEQ in schools and classrooms as they often do not have a mechanical ventilation system or do not operate it to save on electricity bills. However, the measurements and reports from existing research indicate that the indoor air temperatures and CO2 levels are often way outside the recommended values and manual venting by opening windows during breaks is not sufficient. This has become especially alarming during the COVID-19 pandemic, as the virus can spread through the air and under-ventilated classrooms pose a great risk for the pupils located in them. In the scope of this paper, a classroom was simulated concerning IAQ and thermal comfort at various ventilation strategies. The simulation was used to determine the predicted thermal comfort at various locations in the classroom at different window opening areas and orientations. Based on the simulation results potential control strategies for window ventilation were developed. They take into account the changing location of persons and the threshold level of allowed deviation from optimal thermal comfort level to achieve the optimal IAQ as a compromise during the cold winter periods must be made. The results indicated that after 50-second-long natural ventilation at an outside air temperature of -3°C the thermal comfort level will be very low in most of the points of the classroom. None of the various window-opening strategies influences this much. The lowest achieved average PPD was 62.5% and it was in the case when one open window was open at 90° but in the case when two windows were open at 15 cm the average PPD was 98.7%.

1 Introduction

In Latvia, more than 210 thousand pupils are studying in general educational instances. The total number of schools at the start of the year 2021 was 668. Most of these schools are not equipped with mechanical ventilation and rely on natural ventilation by window opening during break times. Installation of mechanical ventilation in education buildings, especially schools, is limited by the construction and architectural specifics of existing buildings. In some cases, air supply vents are installed in windows’ frames or walls. All before mentioned solutions do not ensure the necessary air exchange range as well cause significant discomfort due to the draft. In rooms, without a mechanical ventilation system, mechanical window operation can be introduced with automated control. However, draft and high-temperature asymmetry risks still exist therefore it is necessary to determine what window-opening strategy ensures the best thermal comfort for pupils.

The low ventilation rates can lead to various problems like Sick building syndrome, increased risk of air spread disease transmission and reduction of cognitive performance of pupils [1,2] and others [3–5]. In classrooms, which can be described as densely occupied rooms with relatively high personal activity, ventilation is particularly important for indoor air quality (IAQ).

One of the most commonly used indicators regarding the sufficient ventilation amount is the CO2 concentration as numerous studies have established [6]. Measurements in Latvian education institutions [7,8] have shown that the indoor environment is critical in many classrooms which are not equipped with mechanical ventilation units. In a study [9] it was observed that the concentration of CO2 may have the potential to influence the well-being of the pupil at school, but the correlation is not strong and decisive as many other factors influence the well-being.

Another important aspect regarding the well-being of pupils is Indoor thermal and environmental comfort. This includes parameters like temperature, relative humidity, lighting, noise pollution, smells, and other factors [10]. The concept of Indoor Environment Quality (IEQ) can be grouped into four main categories: thermal comfort, indoor air quality (IAQ), visual comfort, and acoustic comfort [10–12]. One of the main goals of school buildings is to provide children with suitable places for their learning and development [13]. The IEQ must be kept at a high level to obtain the maximal learning capabilities of pupils otherwise, learning and academic activities may be compromised due to discomfort or distraction [1,14–16].

According to various guidance’s on how to operate schools during the COVID-19 they all have in common the general principles: Increase outdoor air ventilation

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but do not open doors to common halls if there are students, decrease occupancy in areas where outdoor ventilation cannot be increased; increase central air filtration or use portable HEPA filters. However, in many cases, these guidelines cannot be implemented and therefore could potentially cause the risk of bad IAQ, as the only possible ventilation is through openable windows. While the outside air temperature during the winter period is very low the ventilation period shortens as the indoor temperature rapidly drops and the classroom is under-ventilated.

To optimize the ventilation systems of naturally ventilated classrooms it is proposed to use automatic control of window opening based on pupil location and IAQ parameters [17]. To achieve it is necessary to define the window-opening principle. This paper studies the influence of window openings on thermal comfort based on CFD simulations. A study [18] showed that CFD can be used for predicting the ventilation performance of school buildings. The results of this study also indicated that double rows windows can help to improve the thermal comfort conditions and so do exhaust fans and ceiling fans. In a different study [19] it was found that CFD is a useful tool for the determination of the effective depth of ventilation. Also, the influence of external louvers on ventilation effectiveness can be studied based on CFD modeling [20].

2 Methods

The purpose of this work is to determine the local and integral characteristics of the air in the classroom with unorganized natural ventilation. To achieve this goal, a set of CAD/CFD programs SolidWorks and FlowSimulation (new name FlowEFD) is used. The SolidWorks CAD program is used to build a simplified three-dimensional model of the classroom, consisting of walls, floor, ceiling, closed door, and three windows.

The dimensions of the analyzed classroom are 6.5m x 7.75 m x 3.35m (height) (see Fig. 1). The maximum number of pupils in the classroom is 24 and one teacher. The room has three windows with a size of 1.40m x 2.13m. The window consists of four sashes: three sashes are deaf, that is, they do not open and one has a tilt-and-turn opening with an area of 650x1350mm (see Fig. 2).

Air exchange in the considered classroom is natural type and occurs due to the difference in temperature between the inside of the room and outside of the building and is influenced by the wind and atmospheric pressure drops. To utilize the usage of such natural ventilation, it is necessary to periodically open windows, vents, and doors to induce air exchange. Such type of ventilation is often found in old houses and schools built in the past 50 years.

The numerical solution of the problem is performed in the CFD program FlowEFD, the problem is considered non-stationary, depending on the given initial and boundary conditions, and reflecting the state of the medium in time. The overall dimensions of the simulated classroom are according to the plans of the real classroom. The three-dimensional model of the classroom is shown in Fig. 3. Furniture and the presence of people in the room were not considered in this work.

2.1 Initial and boundary conditions

Inside the classroom, the initial air temperature $T_v = 21^\circ C$, and the atmospheric pressure $P = 101325$ Pa.

In the further simulation process, three options for opening the sash window were considered (see Fig. 4):

- rotary opening - the window sash is open at an angle of $90^\circ$ from the front surface of the window;
- tilt opening - the window sash is located at a distance of 150 mm from the front surface of the window;
- micro-ventilation - the window sash is located at a distance of 5 mm from the front surface of the window.

**Fig. 4** Window sash opening patterns

Walls, ceilings, floors, doors, and windows are considered a solid body subject to the conditions of adhesion of a viscous liquid when $V_x=V_y=V_z =0$. Heat transfer in a solid body was not taken into account in this problem.

Data on temperature and wind speed were taken as monthly averages for February 2022. Wind speed components are $V_x=0.7\,\text{m/s}$ $V_y=0.4\,\text{m/s}$ at outdoor air temperature $T_{\text{out}}=-3^{\circ}\text{C}$. The worst scenario was considered when the wind blows through the window at a given constant speed. The design diagram of the classroom is shown in Fig. 5. In numerical calculations, the wind speed is considered as a module in the global coordinate system where:

$$|V| = \sqrt{V_x^2 + V_y^2 + V_z^2} = 0.8\,\text{m/c} \quad (1)$$

**Fig. 5** Calculation scheme of the classroom

The parameters in the entire volume of the classroom were determined as the calculation goals: average speed and operating temperature (Operative Temperature), air diffusion efficiency index (ADPI), effective draft temperature (EDT), Local Air Change Index (LACI), and the predicted percentage of dissatisfied (PPD).

Given that the calculations did not consider the presence of people in the room, therefore, the PPD parameter in this paper is informative and will be considered an approximate probabilistic value.

For mathematical modeling of the motion of the medium, the nonstationary Navier-Stokes equations, the energy equation (the first law of thermodynamics), and the equation of steady state were used [21–23].

To find the desired numerical solution to the problem posed, a continuous non-stationary mathematical model of physical processes is discretized both in space and in time, since the movement of a fluid medium is modeled as non-stationary, the solution of stationary problems is defined as a steady state in time.

The formulated system of differential and/or integral equations is nonlinear and in general, does not have an analytical solution. It must therefore be solved numerically. For this purpose, it is necessary to move from differential (integral) equations to their finite difference equivalent. As a result, the mathematical problem of solving the system of differential (integral) equations is reduced to a mathematical problem of solving a system of algebraic equations. Instead of continuously solving the problem, a discrete set of numerical values will be obtained at certain points of space and for certain points in time.

To perform discretization in space, the entire computational area is divided with a computational grid, the faces of which are parallel to the coordinate planes of the Cartesian global coordinate system of the model used in the calculation. The Flow Simulation program uses the finite volume method, the values of all independent variables are calculated at the centers of the cells, and not at the nodes of the computational grid. Accordingly, the cells of the computational grid have the shape of parallelepipeds.

In total, the calculation required 148059 fluid Cells, 58648 solid cells, and 30736 contact cells between the solid and liquid (Partial Cells). An example of a computational grid is shown in Fig. 6.

**Fig. 6** Settlement grid with Finite volume method.

### 2.2 Description of analyzed parameters

Operating Temperature is defined as the uniform temperature of a visually black environment in which the subject will receive the same amount of heat through radiation combined with convection as if he were in an environment with a non-uniform temperature (2).

$$T_c = T_r + T_a \sqrt{\frac{150}{T_a}}, \quad (2)$$
Where: $Tr$ - average radiation temperature, ($^{\circ}$C); $Ta$ - air temperature, ($^{\circ}$C); $v$ - the airspeed, (m/s).

Predicted Percent Dissatisfied (PPD) characterizes the proportion of people who experience discomfort in a given environment. This characteristic has a probabilistic character (it can take values from 5 to 99.9% and is calculated by the formula (3):

$$PPD = 100 - 95e^{-0.03353PMV^4 - 0.2179PMV^2}$$  \hspace{1cm} (3)

Effective Draft Temperature (EDT) is calculated using formula (4):

$$T_d = T - T_m - 7.6553(v - 0.1524)$$  \hspace{1cm} (4)

Where: $T$ - local temperature, ($^{\circ}$C); $T_m$ - average temperature over the considered volume, ($^{\circ}$C); $v$ - local speed, (m/s).

The Air Diffusion Performance Index (ADPI), is defined as the percentage of space in which the air velocity is less than 0.35 m/s, and the effective draft temperature (EDT) is in the range from $-1.7^{\circ}$C to $1.1^{\circ}$C. Local Air Change Index (LACI) is defined as $1/\tau$, where $\tau$ is the dimensionless LMA (Local Mean Time) (5):

$$\tau = \frac{r}{W/Q}$$  \hspace{1cm} (5)

Where: $W$ - the volume of the room (m$^3$), $Q$ - the volumetric flow rate of the fluid entering this room (m$^3$/s).

The average time $\tau$ during which the flow passes from the inlet to any calculated point, taking into account both convection and diffusion, is determined by (6):

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i} \left[ \rho \cdot \tau \cdot u_i - \left( \frac{\mu_t}{\sigma_t} + \frac{\mu_t}{\sigma_t} \right) \frac{\partial \tau}{\partial x_i} \right] = 0$$  \hspace{1cm} (6)

Where: $x_i$ - coordinate of $i$, $\rho$ - density, $u_i$ is the velocity of component $i$, $\mu$ - dynamic viscosity coefficient, $\mu_t$ - the turbulent viscosity coefficient, $\sigma$ and $\sigma_t$ - the laminar and turbulent Schmidt numbers. This equation is solved under the boundary condition $\tau = 0$ at the inlet.

**3 Results**

The calculation results showed that for the case with unorganized natural ventilation in the classroom, the flow rate is uneven and largely depends on the type of window sash opening. In Fig. 7 and further figures, the results of visualization of the flow velocity in the cross-section at the center of the second window (the numbering of the windows is shown in Fig. 5) are shown. In Fig. 7-A situation with a $90^{\circ}$ sash opening of the window is shown. It can be seen that the jet of cold air coming from the street into the warm room of the classroom descends to the floor with maximal velocity and, as it moves away from the window towards the opposite wall, narrows and the velocity decreases. When reaching the opposite wall, the air jet twists, thereby creating a vortex zone. Fig. 7-C shows a variant of the hinged opening of the sash of the second window by 15 cm from the frontal plane of the window, and in Fig. 7-B, for the case of a hinged opening by 15 cm of two windows, the first and second. Here, there is an increase in the flow rate of cold air coming from the street due to the preload of the jet. Cold air moves towards the ceiling and the separation of the flow and the vortex zone for the case shown in Fig. 7-B is around 75% of the width of the room, while for the case shown in Fig. 7-C the depth is about 25%. For micro-ventilation, the window sash is open by 5mm (Fig. 7-D). In this case increase in air velocity is also observed, but at the same time, the separation zone shifts to approximately 10% of the width of the room.
Fig. 7 The results of visualization of the flow velocity in the cross-section in the center of the second window, the estimated time is 50 seconds. a - window 2 is open at 90°, b - Windows 1 and 2 are open at 15 cm, c - window 2 is open at 15 cm, d - window 2 is open at 5 mm.

Table 1. The local average flow velocity in the volume of the classroom

<table>
<thead>
<tr>
<th>Variant</th>
<th>Average velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>window Nr. 2 open 90°</td>
<td>0.11</td>
</tr>
<tr>
<td>windows Nr. 1 and 2 open 15 cm</td>
<td>0.48</td>
</tr>
<tr>
<td>window Nr. 2 open at 15 cm</td>
<td>0.25</td>
</tr>
<tr>
<td>window Nr. 2 open by 5 mm</td>
<td>0.36</td>
</tr>
<tr>
<td>windows Nr. 1, 2 and 3 open 90°</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Fig. 8 The results of visualization of the operating temperature in the cross-section in the center of the second window, the estimated time is 50 seconds. a - window 2 is open at 90°, b - Windows 1 and 2 are open at 15 cm, c - window 2 is open at 15 cm, d - window 2 is open at 5 mm.

In Fig. 9 a graph of the dependence of the change in the local average operating temperature on time over the entire volume of the classroom is presented. It shows how the operative temperature drops in time and the results show that the fastest decline is in the case when all windows are opened at maximum, while in second place is a situation when two windows are opened at a 15 mm incline.

Fig. 9 Changes in local average operating temperature depending on the time at various window opening strategies

Fig. 10 shows the distribution of the LACI characteristic against the background of spatial streamlines. LACI characterizes the ratio of a certain air volume to the volume flow of air passing through this volume. Here, the movement of air is understood as its actual movement together with the flow, as well as the component due to diffusion. As can be seen, the cold air coming from the street reaches the floor Fig. 10-A (for the case of an open window at 90°) or the ceiling of Fig. 10 B-D (for cases of opening windows of 15 cm and 5 mm). Afterward, it heats up due to interacting with warm air, begins to branch, and is divided into several streams, thereby organizing an intense vortex structure.
The change in the local air exchange index over time at different window opening strategies is shown in Fig. 11. It shows that the best ventilation effectiveness is achieved in the case when all windows are maximally opened. In this case, the effectiveness is almost twice as good as in the second-best case which is when only one window is opened to 90°. The worst ventilation is when one window is opened to 15° and nothing changes when two windows are opened to the same opening.

The effective draft temperature is a measure of the difference in temperature between local and average values, taking into account air movement and provided that humidity and radiation are constant in the volume of the room. Studies show that most people in a sitting position feel comfortable if the EDT is in the range from -1.7 °C to 1 °C. Table 2 shows that when opening window nr. 1 and 2 by 15 cm EDT exceeds the allowable range and EDT is -2.53°C. In all other cases, the EDT is within the tolerance range of -1.7°C to 1°C.

### Table 2. The average values of the temperature distribution of the draft throughout the entire volume of the room

<table>
<thead>
<tr>
<th>Variant</th>
<th>Average draft temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>window Nr. 2 open 90°</td>
<td>0.29</td>
</tr>
<tr>
<td>windows Nr. 1 and 2 open 15 cm</td>
<td>-2.53</td>
</tr>
<tr>
<td>window Nr. 2 open at 15 cm</td>
<td>-0.79</td>
</tr>
<tr>
<td>window Nr. 2 open by 5 mm</td>
<td>-1.65</td>
</tr>
<tr>
<td>windows Nr. 1,2 and 3 open 90°</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

The parameter of the Air Diffusion Performance Index describes the proportion of space in which the airflow rate is less than 0.35 m/s, and the temperature of the draft is in the range from -1.7 °C to 1.1 °C. Table 3 shows the values of the air diffusion coefficient. The highest air diffusion coefficient ADPI = 40.22% is in the case when the middle window is opened by 15 cm, while the smallest ADPI = 8.83% is when all windows are opened at 90°.

### Table 3. Air Diffusion Performance Index at various window opening strategies

<table>
<thead>
<tr>
<th>Variant</th>
<th>ADPI [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>window Nr. 2 open 90°</td>
<td>10.98</td>
</tr>
<tr>
<td>windows Nr. 1 and 2 open 15 cm</td>
<td>16.55</td>
</tr>
<tr>
<td>window Nr. 2 open at 15 cm</td>
<td>40.22</td>
</tr>
<tr>
<td>window Nr. 2 open by 5 mm</td>
<td>35.19</td>
</tr>
<tr>
<td>windows Nr. 1,2 and 3 open 90°</td>
<td>8.83</td>
</tr>
</tbody>
</table>

Fig. 12 shows the distribution of the PPD inside the classroom under different window openings. This characteristic is probabilistic and can take values from 5 to 99.9%. The red color shows the zones where the most intense airflow with low temperature is present and the PPD is close to 99.9%. It can be seen that the areas of
discomfort vary depending on the options for opening windows. For example, when window nr. 2 is opened to 90° (Fig. 12-A), the area of discomfort is mostly located at the floor area. When the window is opened to 15 cm (Fig. 12-C) the area of discomfort shifts both toward the floor and towards the ceiling. In case when window 2 is open by 5 mm (Fig. 12-D) the discomfort area shift to the area from the open window to the right as the air velocity is forced to this side.

Fig. 12 Distribution of the allowable percentage of climatic parameters of the environment unsatisfied with uncomfortable conditions PPD. a - window 2 open at 90°, b - window 1 and 2 open at 15 cm, c - window 2 is open at 15 cm, d - window 2 open at 5 mm

A graph of the change in the PPD depending on time, is shown in Fig. 13. The graph shows that the highest expected percentage of unsatisfied environmental conditions will be for the case of two open windows at 15 cm, where the average PPD = 98.7%, and the lowest PPD = 62.5% for the option of one open window at 90°. However, this is the situation after 50-second-long ventilation, and such a short opening time is insufficient to exhaust all pollutants, therefore it can be seen that at -3°C outside air temperature natural ventilation is not a suitable solution.

Fig. 13 Predicted Percent of Dissatisfied over time with various window opening strategies

4 Conclusions

The modeling results showed that the considered classroom with unorganized natural ventilation, at different window operating modes, present uncomfortable thermal comfort. This conclusion is based on several criteria, which are obtained as the results of the simplified numerical calculations.

The results show that more than half of the classroom volume will provide discomfort in case of window ventilation at an outside air temperature of -3°C. And none of the various windows opening strategies influences this much.

Significant unevenness of the indoor climate during the ventilation time is obtained in the simulation results. They show that simultaneously there are zones of both increased and decreased air velocities and temperatures inside the premises. Micro-ventilation (window opening by 5 mm), and folding windows opening by 15 cm, creates an additional factor of discomfort associated with an increase in the speed of cold air coming from the street, associated with a decrease in the window opening area due to jet compression, and its deviation from the normal. There are also large zones of intense vorticity of the airflow.

All obtained thermal comfort and ventilation effectiveness indicators showed that natural ventilation at the assumed outside air temperature and wind velocity significantly lower the comfort conditions inside the
classroom. Therefore, it is recommended to install mechanical ventilation if it is possible. In future works, more scenarios with different outside air temperatures and wind speeds must be simulated to see if there are outside air parameter combinations at whom the natural ventilation is permissible.

The study was supported by the European Regional Development Fund project “Optimal Control of Indoor Air Quality and Thermal Comfort Based on Room Real-time 3D Motion Scanning Data”, Grant Agreement No 1.1.1.1/21/A/010.

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