Whole year simulation of natural and hybrid ventilation performance and estimation indoor air quality for modernized school building

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SUMMARY

Within the Polish - Norwegian project SUREBILD (Sustainable Redevelopment of Buildings) special attention was paid to find the economically feasible technologies that might improve current poor indoor air quality in Polish schools. Detailed analysis has been performed for selected primary school including different scenarios of modernization of ineffective passive stack ventilation system. The results indicated that hybrid ventilation was the most interesting option from energy point of view. The paper describes whole year simulation of natural and hybrid ventilation performance and estimation of indoor air quality. Detailed simulation with 1 min time step was carried out using CONTAMW simulation environment. The comparisons take into account airflows, CO₂ concentrations and perceived air quality expressed in decipol units. Because of huge amount of data the results are partly aggregated by statistical methods.

INTRODUCTION

In order to support theoretical education by practical application, school constructed nowadays usually incorporate elements of sustainable development. However, as 70% of school buildings in Poland are older than 20 years, existing buildings' modernization is the crucial problem. Within the project SUREBILD many potential technologies for sustainable modernization of these schools have been analyzed. Special attention was paid to find the economically feasible technologies that might improve current poor indoor air quality in Polish schools.

Measurements indicate that ventilation rate is typically within the range 2-6 m³/(h pupil) while required value is 20 m³/(h pupil) [1]. Inefficient ventilation systems result in high CO₂ concentrations (up to 4200 ppm) in the classrooms [2]. The project team studied number of different ideas that can improve this situation [3]. A general recommendation for modernization of Polish schools is that more attention should be paid to selection of low polluting finishing materials. In addition, natural ventilation should be supported by adapted mechanical systems in order to assure energy efficiency and comfort irrespective of weather conditions and occupants behaviour. Although the installation of fans and pumps will induce an additional electric energy demand, the possibilities for efficient heat recovery in mechanical systems can reduce the need for heat considerably. Demand control of the ventilation can further improve the energy performance without compromising indoor air quality and comfort.

Although relevant measurements were not carried out in schools in Zgierz, the site inspections, discussions with users and indirect indicators like lower than estimated for
standardized conditions fuel consumption indicate that similar situation is present in this school.

**METHODS**

**Current ventilation system**

At the moment, the school in Zgierz is equipped with ineffective natural ventilation. Fresh air is supplied through leaky windows and then heated within the classrooms by the space heating system. Exhaust air from the classrooms passes into the school hall via transfer grills. Several stacks located in the hall allow the air to leave the building. The cross sections of the transfer grills and the grills mounted in the stacks are strongly reduced by the operating staff partly for energy conservation reasons and partly due to noise transfer.

Indoor air quality is occasionally improved by opening windows in the classrooms (single side ventilation). In winter this procedure is performed during the breaks between lectures. During warm days in spring and autumn windows are also opened during lectures. Because of the climatic conditions in Zgierz (design range of ambient temperature –20 °C to +30 °C), a system based purely on natural ventilation without heat recovery has very poor energy performance during the heating season. However, natural ventilation can be a very good passive mean to provide natural cooling and comfort in the cooling season.

**Concepts for ventilation system modernization**

The initial architectural concept for rehabilitation of the school involves the introduction of a new atrium that would increase the useful floor area in the building [4]. Experiences with energy performance in hybrid ventilated schools in Norway [5] indicate that in order to find the optimal ventilation concept, combined solutions involving both natural and mechanical ventilation should be considered. In the case of Zgierz school, three basic relevant concepts have been analyzed:
- stack based hybrid ventilation with run around heat recovery,
- decentralised mechanical ventilation with high-efficiency heat recovery,
- mixed mode ventilation.

The energy consumption was estimated for these options (taking into consideration additional variants). Basic assumptions for simulations are presented in table 1.

<table>
<thead>
<tr>
<th>Option</th>
<th>Air volume [m³/(h pupil)]</th>
<th>Heat recovery efficiency [%]</th>
<th>Specific fan power [kW/(m³/s)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current situation</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hybrid ventilation</td>
<td>30</td>
<td>~60</td>
<td>0.5</td>
</tr>
<tr>
<td>Decentralized mechanical system</td>
<td>30</td>
<td>&gt;80</td>
<td>2.5</td>
</tr>
<tr>
<td>Mixed mode hybrid ventilation and decentralized mechanical system</td>
<td>30</td>
<td>&gt;80</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The results of the simulations presented in table 2 show that the total primary energy demand (560.4 kWh/m² in the base case) can be significantly (~63%) reduced by thermomodernisation (improved thermal characteristics of the building envelope components,
replacement of old coal fired boilers - average efficiency ~50% - by new energy efficient gas boilers; average efficiency ~95% and reduction of thermal loses in the heating network) and by improving building air tightness (additional 4%). Implementation of hybrid ventilation or mechanical ventilation can also strongly contribute to energy conservation respectively up to 76% and 73.3% respectively. Primary energy calculation were performed using primary resource energy factors: 0 for renewable energies, 0.5 for biomass, 2.5 for electrical power and 1.0 for all other fuels.

Table 2. Energy consumption simulations extended to whole year [6].

<table>
<thead>
<tr>
<th>Case</th>
<th>Heating demand [kWh/m²]</th>
<th>Reduced heating demand relative to base case [%]</th>
<th>Lighting energy demand [kWh/m²]</th>
<th>Fan energy demand [kWh/m²]</th>
<th>Total energy demand [kWh/m²]</th>
<th>Total primary energy demand [kWh/m²]</th>
<th>Reduced primary demand relative to base case [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>209.2</td>
<td>0.0</td>
<td>15</td>
<td>0</td>
<td>224.2</td>
<td>560.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Building rehabilitation</td>
<td>152.9</td>
<td>26.9</td>
<td>15</td>
<td>0</td>
<td>167.9</td>
<td>207.4</td>
<td>63.0</td>
</tr>
<tr>
<td>Infiltration red. from 0.4 to 0.2 ach</td>
<td>133.1</td>
<td>36.4</td>
<td>15</td>
<td>0</td>
<td>148.1</td>
<td>185.4</td>
<td>66.9</td>
</tr>
<tr>
<td>Hybrid not utilizing culvert</td>
<td>81.1</td>
<td>61.2</td>
<td>15</td>
<td>3.1</td>
<td>99.2</td>
<td>135.4</td>
<td>75.8</td>
</tr>
<tr>
<td>Hybrid utilizing culvert</td>
<td>80.4</td>
<td>61.6</td>
<td>15</td>
<td>3.1</td>
<td>98.5</td>
<td>134.6</td>
<td>76.0</td>
</tr>
<tr>
<td>Mechanical ventilation</td>
<td>65.4</td>
<td>68.7</td>
<td>15</td>
<td>15.7</td>
<td>96.1</td>
<td>149.4</td>
<td>73.3</td>
</tr>
<tr>
<td>Mixed mode ventilation (MV/HV)</td>
<td>65.6</td>
<td>68.6</td>
<td>15</td>
<td>9.4</td>
<td>90.0</td>
<td>133.9</td>
<td>76.1</td>
</tr>
<tr>
<td>MV/HV with 0.1 ach infiltration</td>
<td>58.3</td>
<td>72.1</td>
<td>15</td>
<td>9.4</td>
<td>82.7</td>
<td>125.8</td>
<td>77.6</td>
</tr>
</tbody>
</table>

As hybrid ventilation turned out to be very interesting solution, this system has been investigated more detailed. The concept of stack based hybrid ventilation with run around heat recovery applies one or a few central air intakes. Outdoor air passes through refurbished, ground coupled culverts in the basement (figure 1). Axial help fans are placed at the culvert entrances to provide the necessary airflow when natural driving forces are insufficient.

Figure 1. The plan of the basement in primary school in Zgierz after modernization with description of hybrid ventilation – one of the analysed versions [4].
Figure 2. The cross section through two school buildings and the atrium with description of hybrid ventilation – one of the analysed versions [4].

The fans also prevent thermal stratification in the culverts and increase turbulence, resulting in increased convective heat transfer between the supply air and the culvert walls. The air is then filtered before preheating with filters placed at the end of the culverts.

After filtering, the air passes through a first set of heat exchangers connected to similar heat exchangers at roof level via pipes circulating water with some antifreeze solution. The heat exchangers at roof level recover heat from the exhaust ventilation air with an assumed efficiency of 60%. The supply air then passes through a second set of heat exchangers connected to the central (water) heating system in the building, providing the additional heat needed to reach the desired supply air temperature. The air is distributed to the various rooms in the building via horizontal insulated ducts placed in the intake culverts connected to vertical ducts leading up to the various classrooms. The air is distributed into the classrooms via diffusers for displacement ventilation, and is extracted at ceiling level via bypass openings leading to the corridor.

Central air outlets are connected to the first floor corridors. The ventilation air that enters the ground floor corridors enters the first floor corridors via staircases or other bypass openings (figure 2). In addition to the exchangers for heat recovery, the central air outlets are equipped with demand controlled axial help fans. The control of the supply and extract fans are co-ordinated so that the system operates close to balanced mode.

The design of the exhaust tower/chimney should be given special attention in order to utilize wind as a driving force for ventilation, and prevent cold outdoor air from entering and coming in contact with the recovery heat exchanger, which otherwise would reduce the heat recovery efficiency.

It is also essential that the filter and the heat exchangers have large cross sections to ensure that the required airflow rates can be ensured with minimal pressure drop. A similar concept has been successfully applied in many Scandinavian school buildings. However, many of these pilot study projects have unnecessary weaknesses that should easily have been avoided. It is therefore important to take advantage from the knowledge gained from these projects if this concept is to be applied at the Zgierz school.
Indoor air quality assessment

As indoor air quality is generally recognized as the key problem in Polish schools, the assessment of contaminant concentration in modernized school was essential for sustainable redevelopment of Zgierz school. As detailed information about properties of finishing materials that could be used during modernization are not available, carbon dioxide generated during room occupation was selected as the characteristic contaminant. The assessment was performed using computer program CONTAMW ver. 2.4 [7]. CONTAMW is a simulation tool designed to determine:

(a) airflows: infiltration, exfiltration, and room-to-room airflows in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by the indoor and outdoor air temperature difference.
(b) contaminant concentrations: the dispersal of airborne contaminants transported by these airflows; transformed by a variety of processes including chemical and radiological transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces, etc.; and generated by a variety of source mechanisms, and/or personal exposure: the predictions of exposure of occupants to airborne contaminants for eventual risk assessment.

Figure 3 presents the sketchpad of CONTAMW program with zonal representation of Zgierz school. Simulations performed with 10 min time step covered all rooms in modernized school [8].

Figure 3. Zonal representation of Zgierz school (centralized hybrid ventilation option and control system connections); sketchpad of CONTAMW program [8].
RESULTS

The results obtained for selected room at 1 floor (room 0.44) are presented at figures 7 while those obtained for room 1.25 (representative of rooms located at 2 floor) are presented at figure 4. Performed estimations indicated that passive stack ventilation should not be recommended any more for modernization of Polish schools. Even though the classrooms was equipped with 12 vents (at 10 Pa) ventilation intensity is too small and resulting levels of CO₂ are high. Such conditions would result in increased concentrations of other pollutants emitted e.g. from finishing materials. Moreover in case of passive stack ventilation indoor air quality is strongly associated with weather conditions. In both presented classrooms concentrations of pollutants are the highest in June (hot period), and the lowest in January (cold period). It is worth to point out that rooms located at 2 floor due to lower stack heights have generally worse level of indoor air quality.

![Figure 4. Comparison of CO₂ concentration levels in one of classrooms at 1 floor (room 0.40 - left) and in one of classrooms at 2 floor (room 1.27 right) selected day in January (top); Selected day in April (middle) and selected day in June (bottom) [8].](image-url)
On the other hand both mechanical and hybrid ventilation are capable to maintain required air quality within classrooms irrespectively of weather conditions.

Mechanical ventilation is based on constant air volume concept (30 m³/h person) while concept of hybrid ventilation assumes application of control system based on CO₂ concentration. Therefore in some cases the ventilation rates can be lower than minimum 20 m³/h required for every pupil. However these situations are observed only in the morning after start up of the system when air in classrooms is still clean. The tuning of control algorithm in real building could easily reduce number of hours with ventilation rates below minimum rewired values. On the other hand new proposals of EU standards in case of CO₂ based demand controlled ventilation propose the requirements just fore CO₂ concentration not for ventilation rate.

The comparison of distribution of ventilation rates in case of natural ventilation with vents and for hybrid ventilation is presented at figure 5 (for mechanical ventilation air flow rates are constant). These figures represents data obtained for room 1.43 at 2 floor. The graphs once again indicates that natural ventilation does not provide enough fresh air to the classrooms. In analyzed classroom minimum ventilation rates per person are never reached, and moreover during almost 30% of time air flows has reversed direction (air supply through transfer grills and exhaust through vents in windows. This phenomenon is not observed in case of hybrid
ventilation. It should be pointed out that very low ventilation rates are observed just after pupils enter the classroom. When sensors measure increased concentration of CO₂ ventilation rates are increased.

Figure 6 presents the example of simulations of perceived air quality (assumed emission from finishing materials 0.1 olf/m²). It can be observed that PAQ can be lowered from ~8 decipol to 3 decipol that could lead to reduction of percentage of dissatisfied visitors from 57 to 33%.

**DISCUSSION**

The IAQ analysis indicated that both solutions mechanical ventilation and hybrid ventilation can be regarded as very close to optimal option of ventilation for Zgierz school. Differences between mechanical and hybrid ventilation are the result of applied CO₂ based demand controlled strategy for ventilation intensity and assumed levels switching between speed of fans. The great improvement in IAQ can be obtained together with significant reduction of primary energy use of the school. The results are based on analysis of just one school. However, this object is representative for hundreds of schools erected in sixties in XX century. Similar analysis of these schools would thus probably lead to resembling conclusions.

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