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The Indoor Environment Quality of Primary School Buildings

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ABSTRACT

This dissertation explores the design and simulation of decentralized ventilation systems for primary schools, emphasizing enhancing indoor air quality (IAQ) and energy efficiency. The study employs computational fluid dynamics (CFD) simulations to analyse the temperature progression and heat transfer efficiency within heat recovery units (HRUs) under different seasonal conditions. These simulations identify potential areas for efficiency improvements and validate the effectiveness of the HRUs in maintaining optimal IAQ.

The research also includes experimental measurements of thermal comfort and IAQ in primary schools across Slovakia, Sweden, and the United Arab Emirates (UAE). These measurements assess the performance of current ventilation systems and verify the recuperation efficiency of HRUs. The findings demonstrate significant improvements in energy efficiency and IAQ, offering practical recommendations for implementing effective ventilation strategies in school buildings.

ABSTRAKT

Táto dizertačná práca skúma návrh a simuláciu decentrálnych (lokálnych) vzduchotechnických systémov pre základné školy so zameraním na zlepšenie kvality vnútorného ovzdušia a energetickej efektívnosti. Štúdia využíva CFD simulácie výpočtovej dynamiky tekutín na analýzu progresie teploty a účinnosti prenosu tepla v rekuperačných jednotkách tepla za rôznych sezónnych podmienok. Tieto simulácie identifikujú potenciálne oblasti na zlepšenie účinnosti a overujú účinnosť HRU pri udržiavaní optimálnej kvality vnútorného ovzdušia.

Výskum zahŕňa aj experimentálne merania tepelného komfortu a kvality vnútorného ovzdušia na základných školách na Slovensku, vo Švédsku a v Spojených Arabských Emirátoch. Tieto merania hodnotia výkon súčasných ventilačných systémov a overujú účinnosť rekuperačných jednotiek. Zistenia preukazujú významné zlepšenia energetickej efektívnosti a kvality vnútorného ovzdušia a ponúkajú praktické odporúčania na implementáciu účinných ventilačných stratégií v školských budovách.

CONTENTS

INTRODUCTION

School buildings often suffer from poor thermal insulation and lack mechanical ventilation systems, relying solely on natural ventilation through windows. This method is inadequate today and is sometimes prohibited for safety reasons. The indoor environment quality of schools directly affects the concentration and attention of teachers and students. According to Act no. 355/2007 Coll., facilities for children should be health-friendly and free from harmful factors like noise and air pollution.

Most school buildings were constructed in the last century, and although some have been renovated, indoor microclimate conditions remain unsatisfactory. Proper classroom functioning requires suitable microclimate conditions, which natural ventilation alone cannot ensure, especially in busy areas. This method is also inefficient for energy savings and exposes children to temperature fluctuations and diseases during cold months.

1 STATE OF THE ART – VENTILATION OF SCHOOL BUILDINGS

A healthy school environment is essential for children's growth, learning, and social development. In Europe, over 64 million students and nearly 4.5 million teachers spend significant time in indoor school environments, exposing them to poor air quality which negatively impacts health, causing respiratory issues, cardiovascular disease, and cancer (WHO, 2005, 2009, 2010, 2021). Pollutants like particulate matter (PM), carbon dioxide (CO_2), and volatile organic compounds (VOCs) are linked to these health problems (EPA, 2021).

The Parma Declaration by WHO Europe in 2010 urged actions to improve air quality in schools (WHO, 2010). The SINPHONIE project monitored school environments and children's health across 23 European countries, developing guidelines for healthier schools (SINPHONIE, 2015). Improved ventilation rates in classrooms can enhance student performance by up to 15% (Wargocki and Wyon, 2013). Standards like ASHRAE Standard 62.1 recommend minimum ventilation rates to ensure acceptable air quality (ASHRAE, 2019). WHO and the European Commission emphasize ventilation to mitigate airborne disease transmission in schools (WHO, 2020; European Commission, 2021).

Ventilation methods include natural ventilation, mechanical ventilation, and hybrid systems. Recent advancements, such as demand-controlled ventilation (DCV), energy recovery ventilation (ERV), and advanced filtration systems, improve indoor air quality while minimizing energy use (Laverge et al., 2011; Dodoo et al., 2011; Zhang et al., 2011). Challenges include the cost of advanced systems, maintenance needs, and architectural design of school buildings (Mumovic et al., 2009; Clements-Croome, 2000). Federal funding helps schools implement ventilation upgrades, reducing disease transmission and improving health outcomes (CDC, 2022, 2023).

2 LEGISLATION, REGULATIONS AND TECHNICAL STANDARDS

Microclimate conditions for school buildings are regulated by several key documents.

Slovakia Legislation

- **Decree No. 259/2008 Coll.:** Sets parameters for school microclimates, specifying temperatures and air exchange rates for different areas.
- **Decree No. 527/2007 Coll.:** Details requirements for heating and air exchange, ensuring classrooms maintain at least 20 °C, and outlines air exchange rates (e.g., 20 – 30 m^3/h per student in classrooms).
- **Other relevant acts:** Include noise, infrasound, and vibration limits, fire safety requirements, and protections against chemical exposure.

Legislation Abroad

- **Czechia:** Decree No. 160/2024 Coll. specifies ventilation and microclimate parameters, and Decree No. 268/2009 Coll. ensures hygienic air parameters and safe, economical operation of ventilation systems.

WHO Guidelines and EU Initiatives

- **WHO guidelines:** Focus on indoor air quality (IAQ), covering pollutants and risks associated with humidity and biological agents.
- **EU member states actions:** Some countries adopt IAQ guide values, national plans, and monitoring activities.

Recommended technical standards

- **STN EN 16798:** Specifies indoor environmental parameters for buildings, addressing IAQ, thermal environment, lighting, and acoustics.
- **Other standards:** Include calculations for heat loads, air conditioning measurements, and ventilation requirements (e.g., STN 73 0548, STN EN 13779, and STN EN 15251).

European standards and technical commissions (CEN/TC 113, CEN/TC 156, CEN/TC 195) develop and adopt standards into the Slovak system. The National Technical Commission TK 59 ensures the relevance and development of Slovak standards, addressing specific national needs.

3 FACTORS AFFECTING THERMAL COMFORT AND IAQ

Outdoor environmental factors

External environmental factors depend on climate, location, time of year, and pollutant production. These affect both outdoor and indoor environments in buildings (Smojlík, 1985). Key factors include:

- **Sunlight:** Influences thermal load on buildings, with 43% of solar radiation reaching the Earth's surface (Knapp, 2011).
- **Temperature:** Varies with geographical location and time, influencing building design (Smojlík, 1985).
- **Humidity:** Relative humidity impacts comfort and work performance, with optimal ranges between 30-70% (Decree No. 527/2007 Coll.).
- **Air pressure:** Fluctuates due to weather changes, influencing ventilation design.
- **Airflow:** Determined by pressure differences and wind speed, increasing with altitude (Smojlík, 1985; Forejt and Hemerka, 2011).

Indoor environmental factors

Indoor environmental parameters are defined in STN EN 16798 and include thermal environment, IAQ, humidity, lighting, and noise. Thermal comfort depends on:

- **PMV/PPD indices:** Predict thermal sensation and dissatisfaction (ISO 7730, 2005).
- **Physical activity and clothing:** Influence thermal comfort (ASHRAE Standard 55, 2023).

IAQ and ventilation rates

IAQ is controlled through source control, ventilation, and filtration. Proper design ventilation airflow rates are essential for maintaining IAQ (Székyová et al., 2024; Gebauer et al., 2007).

Indoor air pollutants

Common pollutants in classrooms include CO_2, NO_2, PAHs, radon, VOCs, and particulate matter ($PM_{2.5}$ and PM_{10}), which can impact health and performance. Poor IAQ affects students' attention and academic outcomes (Pulimeno et al., 2020). Limits for these pollutants are specified in various regulations (Decree No. 259/2008 Coll., STN EN 16798-1:2019).

4 VENTILATION AND AIR CONDITIONING

Natural ventilation

Natural ventilation relies on natural forces like gravity and wind to move air. It includes:

- **Infiltration:** Air moves through porous materials and gaps in windows/doors (Gebauer et al., 2007).
- **Window ventilation:** Uses pressure differences created by wind and temperature (Székyová et al, 2004).
- **Solar chimneys:** Enhance natural ventilation using solar energy to increase airflow.

Mechanical ventilation

Mechanical ventilation uses fans to move air, independent of external conditions (Gebauer et al., 2007). Advantages include:

- **Air treatment:** Air can be filtered, heated, cooled, and humidified.
- **Control:** Allows regulation of air quality and pressure within buildings.

Air conditioning systems

Air conditioning systems maintain indoor climates by controlling temperature, humidity, and air quality. They can be centralized or decentralized:

- **Centralized systems:** Provide whole-building ventilation through ductwork, ideal for new constructions (Székyová et al, 2004).
- **Decentralized systems:** Use smaller units for specific areas, suitable for retrofits and solving localized issues (Gebauer et al., 2007).

Hybrid ventilation

Combines natural and mechanical methods, using low-pressure fans to assist when natural forces are insufficient. It balances ease of installation, energy savings, and reliable performance. Effective ventilation and air conditioning systems are crucial for maintaining healthy and comfortable indoor environments in school buildings (Gebauer et al., 2007).

5 AIMS AND METHODOLOGY OF THE THESIS

5.1 Aim of the thesis

The dissertation aims to:

1. Simulate air flow temperature in a ventilation recovery unit.
2. Verify simulation outputs with experimental measurements and assess heat recovery efficiency.

3. Measure indoor air quality in school classrooms to evaluate the sufficiency of natural ventilation and compare with schools in different climates.
4. Map current classroom ventilation in Slovakia and abroad, defining indoor air quality requirements through legislation and standards.

5.2 Methodology of the thesis

The thesis employs the following methods:

1. Use CFD software to model airflow and temperature in the HRU, running simulations under various conditions, and validating results against theoretical predictions and previous studies.
2. Set up an experimental rig to measure actual temperature waveform and airflow, comparing results with simulations and manufacturer specifications to evaluate heat recovery efficiency.
3. Equip classrooms with monitoring devices to measure CO_2, temperature, RH, and particulate matter, collecting data over time and comparing it with classrooms in different climates to assess natural ventilation.
4. Distribute surveys to schools in Slovakia and abroad, gather information on ventilation systems and standards, and synthesize findings to define optimal indoor air quality requirements for classrooms.

6 SIMULATIONS OF TEMPERATURES PROGRESSION OF AIRFLOW IN HEAT RECOVERY UNIT

Heat recovery units (HRUs) enhance HVAC system energy efficiency by transferring heat between incoming and outgoing air streams, conserving energy and improving indoor air quality (IAQ). This chapter presents CFD simulations using Ansys Fluent to analyse temperature progression in HRUs.

6.1 Aim of simulation

The simulation aims to analyse the temperature progression of airflow within a heat recovery exchanger, optimize design for maximum energy recovery, and improve HVAC system performance.

6.2 Simulation methodology

Key parameters observed include:

- **Temperature distribution:** inlet and outlet temperatures, temperature contours.

- **Heat transfer:** rate between airflows, local and overall heat transfer coefficients.
- **Performance metrics:** effectiveness and thermal efficiency.

Mathematical model and simulation mesh network

The SST k-ω model was used for accurate simulation of near-wall and free-stream conditions. Transport equations for turbulent kinetic energy (k) and specific dissipation rate (ω) were utilized.

An unstructured mesh with varying resolution was used to balance accuracy and computational load, focusing on critical areas with high gradients.

6.3 Results and evaluation of simulations

Summer operation

Figure 6.1 shows the summer operation simulation of the HRU, with warm air (red/orange) entering from one side and cooler air (blue) from the opposite, displaying a heat transfer gradient within a temperature range of 27.99 °C to 35.06 °C.

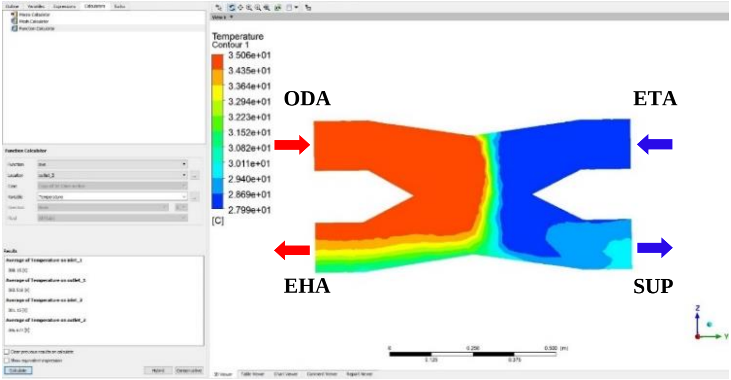


Fig. 6.1 Simulation of summer operation of the HRU

Winter operation:

Figure 6.2 shows the winter operation simulation of the HRU, with cold air (blue/cyan) entering from one side and warm air (red/orange) from the other, displaying a clear heat transfer gradient within a temperature range of -11.26 °C to 20.06 °C.

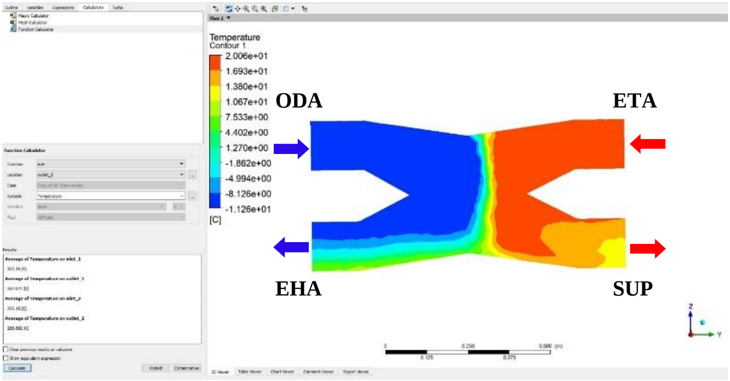


Fig. 6.2 Simulation of winter operation of the HRU

Key observations: Effective heat transfer indicated by temperature gradients.

6.4 Discussion and conclusion

The simulations confirmed the HRU's design and functionality, demonstrating effective heat transfer. Challenges included high-resolution mesh requirements and ensuring convergence. Future work should enhance the model, incorporate real-world data, and explore different turbulence models for improved accuracy. This study underscores the importance of CFD simulations in optimizing HRUs for more efficient HVAC systems.

7 EXPERIMENTAL MEASUREMENT N° 1 – MEASUREMENT OF THE PHYSICAL PROPERTIES OF THE HRU

7.1 Aim of simulation

The experimental measurements aimed to verify the efficiency of the HRU as specified by the manufacturer, which was 96%, under real conditions and to measure airflow temperatures.

7.2 Measurement methodology

The experimental measurements focused on the airflow temperatures (ODA, SUP, ETA, and EHA) and the surface temperature of the heat exchanger in the HRU. The surface temperature was measured using CRZ2005R-100 temperature sensors, also known as PT100, connected to the DAQ970A data acquisition system. These measurements were conducted from January 17th to March 1st, 2024, with a 3-min time resolution. On January 25th, two additional temperature sensors were added to the surface of the HRU.

The measurements took place in the heavy laboratory pavilion of the Faculty of Mechanical Engineering. The HRU was connected to the exterior via a flexible duct Sonodec 160, with supply air delivered through a Spiro 160 duct. Twelve CRZ2005R-100 temperature sensors were positioned around the HRU to capture the necessary data (Fig. 7.1).

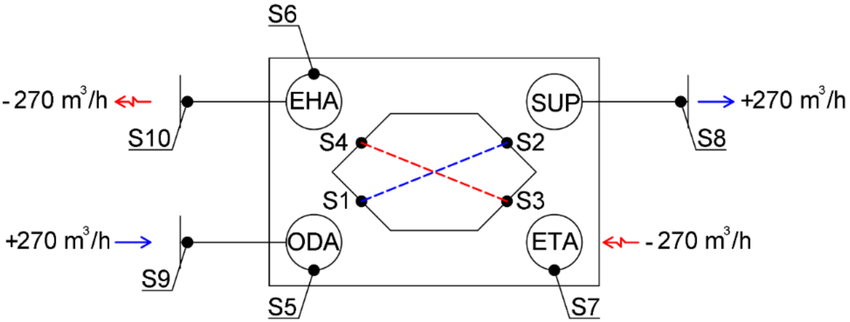


Fig. 7.1 Simplified scheme of placement of the sensors on the HRU

7.3 Results and evaluation

The recorded waveforms of the physical parameters measured are shown in Fig. 7.2, highlighting the HRU's performance over time. Using the ASHRAE 84 (2020) simplified equation, the efficiency of the HRU was calculated to be 89 %.

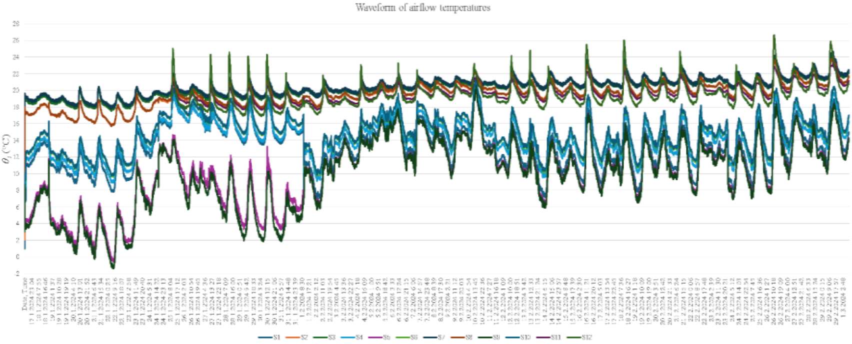
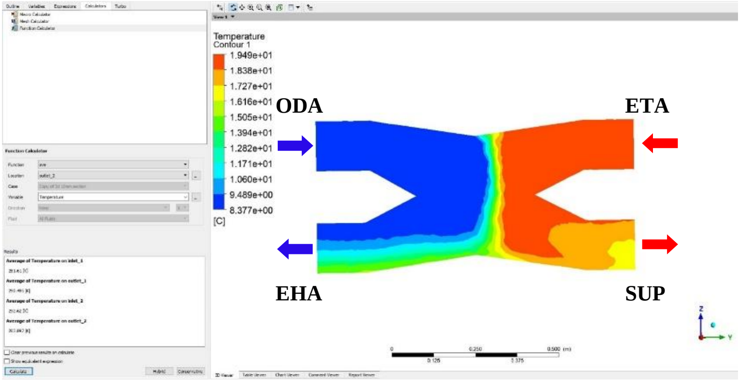


Fig. 7.2 Airflow temperatures – from 17th of January to 1st of March

A CFD simulation based on data from February 1st demonstrated a temperature gradient ranging from 8.377 °C to 19.49 °C, indicating effective heat transfer with an efficiency of 80 % (Fig. 7.3).



Function Calculator

Function: ave

Location: outlet_2

Variable: Temperature

Results

Average of Temperature on inlet_1

Average of Temperature on outlet_1

Average of Temperature on inlet_2

Average of Temperature on outlet_2

☐ Clear previous results on calculate

☐ Show equivalent expression

Fig. 7.3 Simulation based on experimental measurements

7.4 Discussion and conclusion

The experimental efficiency of the HRU was found to be 89 %, lower than the manufacturer's claimed efficiency of 96 %. This discrepancy aligns with findings from other studies, which show that real-world conditions often reduce efficiency. The study emphasizes the importance of experimental validation and suggests that manufacturers should provide more conservative efficiency estimates. Combining experimental data with CFD simulations provides comprehensive insights into HRU performance, crucial for optimizing energy recovery in building ventilation systems. Future research should focus on the long-term performance of HRUs under various operational conditions and investigate methods to reduce the gap between theoretical and actual efficiencies.

8 EXPERIMENTAL MEASUREMENT N° 2 – THERMAL COMFORT AND IAQ IN SCHOOLS

8.1 Aim of measurement

The aim was to measure the thermal environment and IAQ in primary schools in Slovakia, Sweden, and the UAE over five school days during the heating season. Slovakia and UAE had 15 classrooms each, while Sweden had 45 classrooms. Schools were selected based on climate, ventilation systems, and year of construction.

8.2 Measurement methodology

The measured parameters included temperature, relative humidity (RH), CO_2, NO_2, O_3, TVOC, C_1 – C_{10} aldehydes, and particulate matter (PM_{10}

and $PM_{2.5}$). A survey gathered students' subjective evaluations of thermal comfort.

Indoor air temperature, RH, and CO_2 were measured with Vaisala GMW 90R monitors and HOBO data loggers in Slovakia and UAE, and Wöhler CDL210 in Sweden. NO_2 and O_3 were sampled with passive/diffusive samplers, while VOCs were sampled on Tenax TA adsorbent tubes. Aldehydes were sampled using DSD-DNPH Aldehyde Diffusive Sampling Devices. PM10 and PM2.5 were measured using TSI DustTrak DRX and Flow sensors.

Instruments were placed on shelves or cabinets away from direct heat sources and solar radiation. Air pollutant samplers were placed about 50 cm from the ceiling.

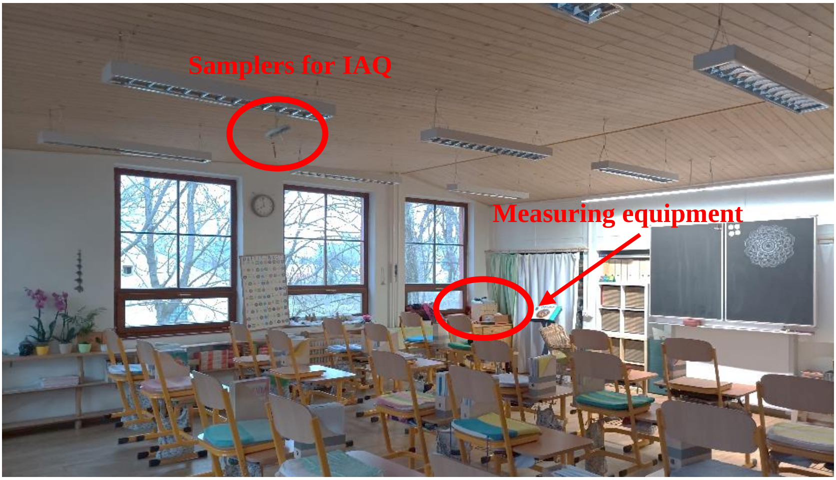


Fig. 8.1 Placement of measuring devices

8.3 Results and evaluation

The study revealed significant variations in IAQ and thermal comfort across the countries:

Sweden: Showed the best IAQ with CO_2 levels ranging from 450 ppm to 960 ppm, indicating effective mechanical ventilation. Particulate matter levels remained within acceptable limits.

Slovakia: Had higher CO_2 levels (895 ppm to 1904 ppm) due to inadequate natural ventilation, with particulate matter often exceeding WHO guidelines.

UAE: CO_2 levels varied widely, with some classrooms reaching 4095 ppm during occupied times. High particulate levels were influenced by outdoor dust and insufficient air purification.

Figures Fig. 8.2 – Fig. 8.7 show comparative statistics for the three monitored countries.

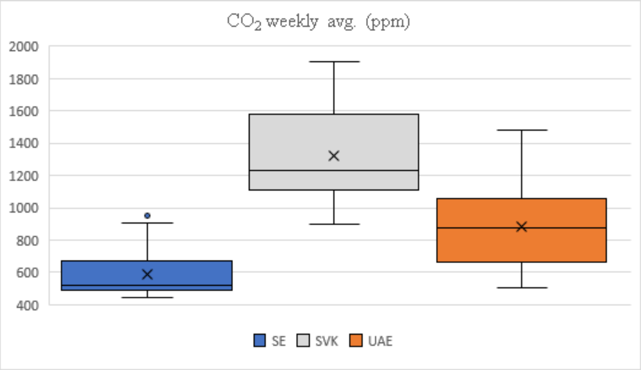


Fig. 8.2 Weekly average CO_2 concentrations in the classrooms

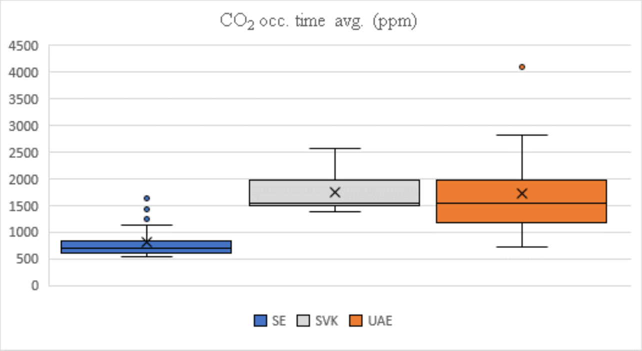


Fig. 8.3 Occupied time average CO_2 concentrations in the classrooms

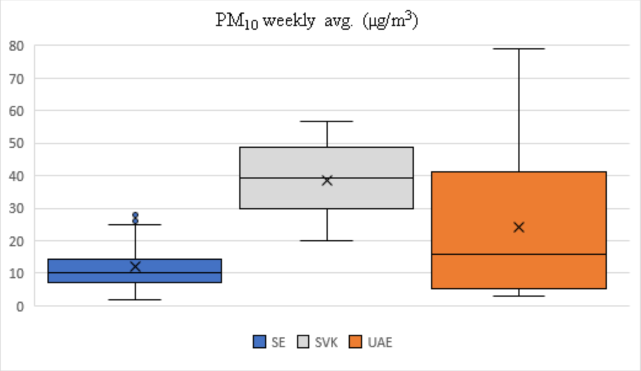


Fig. 8.4 PM_{10} concentrations based on weekly averages in the classrooms

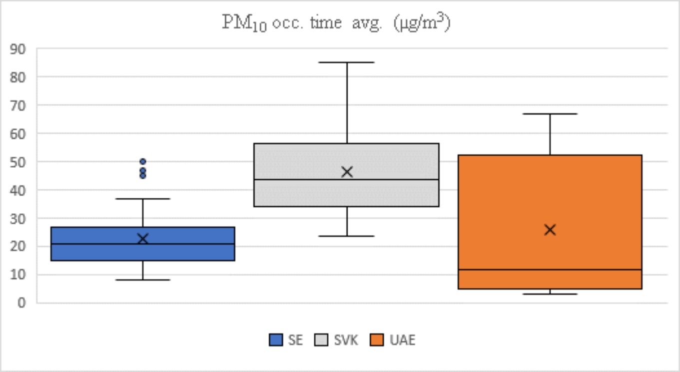


Fig. 8.5 PM$_{10}$ concentrations based on occupied time averages in the classrooms

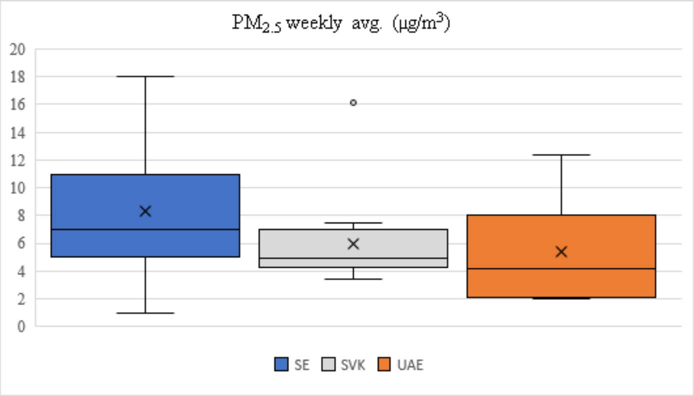


Fig. 8.6 PM$_{2.5}$ concentrations based on weekly averages in the classrooms

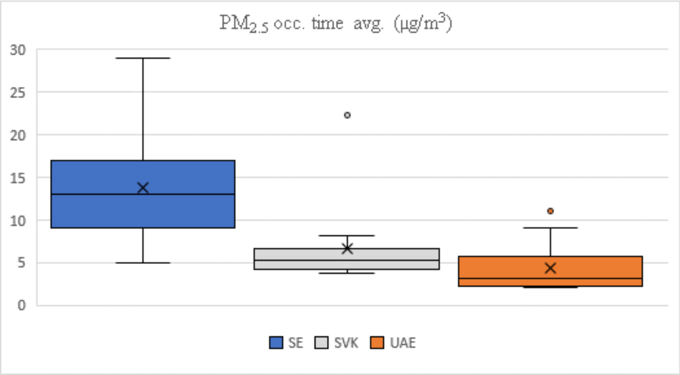


Fig. 8.7 PM$_{2.5}$ concentrations based on occupied time averages in the classrooms

Survey results

The survey results provided insights into students' perceptions:

- **Thermal comfort**: Fewer students in UAE schools felt thermally comfortable compared to those in Sweden and Slovakia. In the UAE, 34 % felt too warm or cold, while 78 % in Sweden and 81 % in Slovakia felt neutral.
- **Air quality**: Most students perceived air quality as "OK." However, more UAE students (35 %) rated it as good compared to Sweden (22 %) and Slovakia (8 %).
- **Overall Environment**: Noise was a concern across all countries, but bad smells and lighting were less problematic. Slovak classrooms had slightly worse conditions for bad smells.

8.4 Discussion and conclusion

This study reveals significant differences in IAQ and thermal comfort across schools in Sweden, Slovakia, and the UAE, driven by the type of ventilation systems and local climates.

The study emphasizes the importance of effective ventilation systems for maintaining IAQ and thermal comfort in schools. Sweden's mechanical ventilation outperformed the systems in Slovakia and the UAE, underscoring the need for improved ventilation infrastructure, especially in regions with inadequate systems.

9 BENEFITS OF THE DISSERTATION

This chapter outlines the various benefits derived from the dissertation, emphasizing contributions to scientific advancement and practical applications, particularly in improving indoor environmental quality in primary schools.

9.1 Benefits for the development of science

Innovative methodologies: The dissertation introduces advanced CFD simulations to analyse temperature progression and heat transfer efficiency in HRUs. This enhances the current methodologies in HVAC system analysis, offering a more accurate understanding of thermal dynamics and potential efficiency improvements.

Empirical validation: The research combines simulations with experimental measurements, validating theoretical models with real-world data. This dual approach ensures the reliability and applicability of findings, contributing to robust scientific knowledge in the field of HVAC systems.

Cross-regional analysis: The study compares IAQ across different climates in Slovakia, Sweden, and the UAE, providing insights for region-specific solutions and contributing to global HVAC system knowledge.

9.2 Benefits for Practice

Enhanced indoor air quality: The findings offer strategies to improve IAQ in primary schools, leading to healthier, more comfortable environments for students and staff, and contributing to better cognitive function and reduced absenteeism.

Energy efficiency and sustainability: By optimizing HRU performance, the research supports significant energy savings and long-term sustainability goals, providing a model for other public buildings.

Policy and standards development: The insights can inform policymakers and standard-setting bodies to update regulations and develop guidelines that ensure healthier and more sustainable school environments globally.

CONCLUSION

In conclusion, this thesis has examined thermal comfort and IAQ in primary schools in Sweden, Slovakia, and the UAE, highlighting significant regional differences due to climate, building design, and ventilation systems. Swedish schools had superior IAQ and thermal comfort due to advanced mechanical ventilation, while Slovak and UAE schools struggled with poor IAQ, particularly in managing CO_2 and particulate levels. The study underscores the importance of advanced ventilation systems in ensuring optimal IAQ and advocates for their adoption in regions with extreme climates or outdated infrastructure. The integration of CFD simulations provided valuable insights into improving HRU efficiency, guiding future upgrades to school ventilation systems. These findings offer a foundation for future research and policy development, promoting healthier and more conducive learning environments globally.

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The rest of the references can be found in the Dissertation thesis.

Zoznam publikačnej činnosti

V2 Vedecký výstup publikačnej činnosti ako časť editovanej knihy alebo zborníka

V2_01 STRAKOVÁ, Zuzana - ŠTEFANIČ, Pavol. Požiadavky na vnútornú mikroklímu v priemyselnom stavebnom objekte. In Vzduchotechnika 2020 : zborník prednášok. 26.-27. október 2020, Nový Smokovec - Vysoké Tatry. 1. vyd. Bratislava : SSTP, 2020, s. 56-59. ISBN 978-80-89878-64-2.
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Kategória publikácie do 2021: AFD

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Typ výstupu: článok; Výstup: zahraničný; Kategória publikácie do 2021: ADE

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Typ výstupu: príspevok z podujatia; Výstup: zahraničný; Kategória publikácie do 2021: BEE

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Typ výstupu: článok; Výstup: domáci; Kategória publikácie do 2021: BDF

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