The 21st International Conference on
Thermal Science and Engineering of Serbia
SimTerm 2024
Niš, Serbia, Oct 22-25 2024
doi: 10.5937/SimTerm24204M

Air-conditioning Control Strategies for an Amphitheater for Different Occupancy Scenarios

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Abstract: This work focuses on the ventilation control strategies employed in Amphitheater A at the Faculty of Mechanical Engineering, University of Belgrade, Serbia with a particular emphasis on occupancy-based control. Given the amphitheater's high occupancy capacity of up to 500 people and variable usage patterns, designing an efficient ventilation system is essential for maintaining optimal indoor air quality and minimizing energy use. The study explored the implementation of Constant Air Volume (CAV) and Variable Air Volume (VAV) systems, with ventilation controlled by mean indoor air temperature and CO_2 concentration. Various occupancy scenarios were simulated using the IDA ICE software to assess how each control strategy maintains indoor air quality under different conditions. The simulation results revealed significant differences in the performance of the CAV and VAV system. The VAV system, particularly when controlled by temperature allowed for precise adjustments of ventilation rates based on real-time usage, reducing energy use during periods of lower occupancy. In contrast, the CAV system, while maintaining constant airflow, showed higher energy use, due to its inability to adjust dynamically to change in occupancy levels. Overall, this paper provides valuable insights into the benefits of demand-controlled ventilation based on occupancy in large spaces.

Keywords: Ventilation Control, Occupancy, Constant Air Volume (CAV), Variable Air Volume (VAV), Energy Efficiency

1. Introduction

This paper aimed to provide a comprehensive analysis for ventilation control strategies and their impact on indoor air quality and thermal comfort in Amphitheater A at the Faculty of Mechanical Engineering, University of Belgrade. The simulations were conducted using IDA ICE 5.0, a software developed by EQUA, which offers advanced capabilities for evaluating the energy performance of buildings [1]. Given the amphitheater's large capacity and varying occupancy rates, maintaining optimal indoor air quality and thermal comfort presents a significant challenge, especially during periods of high usage.

The study focused on the implementation of Constant Air Volume (CAV) and Variable Air Volume (VAV) systems [2], which are commonly used in large public spaces to manage ventilation. Both systems were tested under different control strategies, specifically based on CO_2 levels and mean air temperature. The CO_2 level and the mean air temperature measured in the exhaust duct were used as a signal for these control strategies and they played a critical role in ensuring that air quality and overall comfort of occupants remained within acceptable limits while minimizing energy use.

Integrated Dynamic Analysis of Indoor Climate and Energy (IDA ICE) is a program for study of the indoor climate of individual zones within a building, as well as energy use for the entire building. IDA Indoor Climate and Energy is an extension of the general IDA Simulation Environment. This means that the advanced user can, in principle, simulate any system whatsoever with the aid of the general functionality in the IDA environment.

Through a series of detailed simulations, the study evaluated the indoor air quality and the overall energy performance of the ventilation systems in Amphitheater A. Various occupancy scenarios were considered to mimic the real-life usage patterns of the amphitheater, ranging from partial to full capacity. The results of the study provide valuable insights into how these systems can be optimized to balance energy efficiency with occupant comfort, offering practical recommendations for improving ventilation strategies in similar large-scale spaces.

2. Methodology

The methodology involved building a detailed model in the simulation software, followed by running simulations to identify which ventilation strategy provided the best results in terms of energy efficiency and thermal comfort for the occupants. In all strategies, the regulation of air temperature was achieved by the cooler supply airflow.

2.1 Data collection

Different information about the Amphitheater A were collected to provide resource for the simulation using IDA ICE software. simulate. The amphitheater was modeled based on precise geometric details and it was designed as a single thermal zone. Internal structures adjacent to the neighboring rooms and external walls exposed to the environment were assigned distinct heat transfer coefficients.

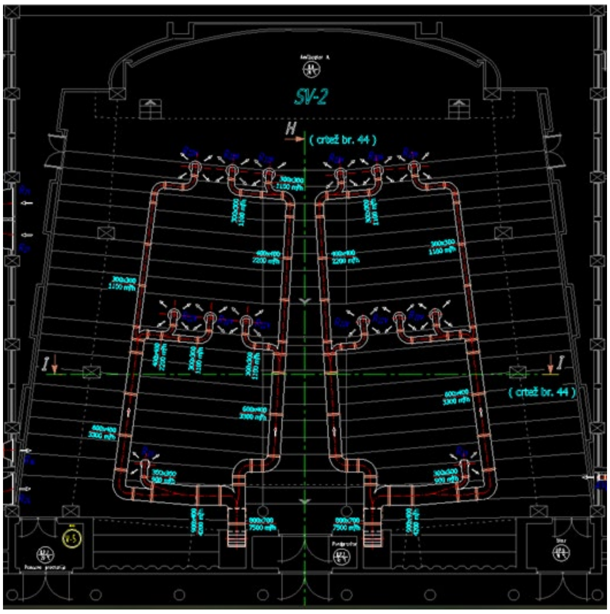


Figure 1. The CAD drawing

The building geometry of the amphitheater as shown in Figure 1. was modeled. The dimensions of the amphitheater were extracted from a vector file, which provided precise geometric data. This file contained detailed information about the layout and structural elements of the space, enabling accurate modeling. These extracted dimensions offer a comprehensive understanding of the amphitheater, ensuring that the simulation faithfully represents the physical characteristics of Amphitheater A. This accuracy allows for more reliable assessments of ventilation strategies and their impact on indoor air quality and energy performance. The placement of anemostats, as shown in Figure 1, was not specified in the software due to the irrelevance of their exact position, as they are automatically added.

To simulate the building construction, the heat transfer properties, U-values, were defined for different surfaces. For instance, for external walls a U-value of 1.45 W/m²K was set, for internal walls and doors 1.3 W/m²K was set, and the for the single-pane glazing windows a U-value of 5.8 W/m²K was set. Although thermal bridges are acknowledged, they were considered insignificant for the heat load calculations and are disregarded in the model. The thermal load was calibrated with the previous design calculation shown in Table 1. These calculations were essential for determining the heat gains and losses within the amphitheater but are outside the scope of this study, which focuses specifically on the ventilation control strategies and their impact on indoor air quality and energy efficiency. The total heat load, the sum of all previously calculated loads, are presented in Table 1. [3]

To simulate an air handling unit (AHU) the following information were used. Figure 2 shows the simulated AHU. The AHU consists of a heat recovery wheel, a mixing box, a heating coil, a cooling coil, and supply and exhaust fans. This configuration allows a 5 K temperature rise where, with variable water flow enabling the air to reach the setpoint of 16° C. Considering a 1 K temperature rise in the ducts, representing losses, the supply air temperature is set at 17° C. The mixing box maintains a constant fresh air-to-exhaust air ratio of approximately 80%, and its effects on energy use will not be addressed in this paper. The rotary heat exchanger operates at an efficiency of 0.85.

Table 10. The total heat load calculation

Total heat load													
time [h]	8	9	10	11	12	13	14	15	16	17	18	19	20
QOccupancy	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000	35000
QLights	352.224	2054.64	2142.696	2201.4	2260.104	2318.808	2377.512	2406.864	2465.568	2494.92	2524.272	2553.624	2582.976
Q_{Rooms}	4784	4784	4784	4784	4784	4784	4784	4784	4784	4784	4784	4784	4784
$Q_{equipment}$	0	0	0	0	0	0	0	0	0	0	0	0	0
Q_{walls}	3534	3361	3384	3578	3936	4389	4987	5659	6414	7108	7709	8176	8430
$Q_{windows}$	218	799	1343	1743	2142	2396	2505	2542	2505	2324	1997	1525	1053
$Q_{Solar\ radiation}$	2480	2107	1809	1925	2347	2807	3153	3307	3194	2889	2355	1783	1403
sumQ	46368.224	48105.64	48462.696	49231.4	50469.104	51694.808	52806.512	53698.864	54362.568	54599.92	54369.272	53821.624	53252.976

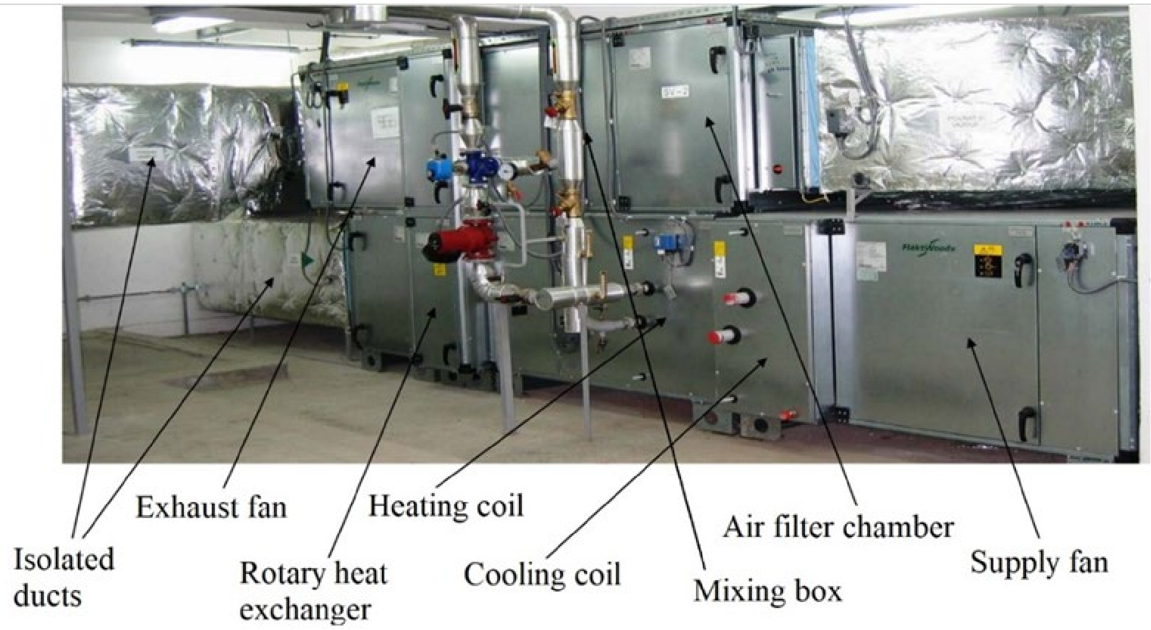


Figure 2. The air handling unit

2.2 Simulation model

In Figure 3, some areas of the zone envelope are shown in white, representing internal structures, while the darker shades indicate external walls and the rooftop.

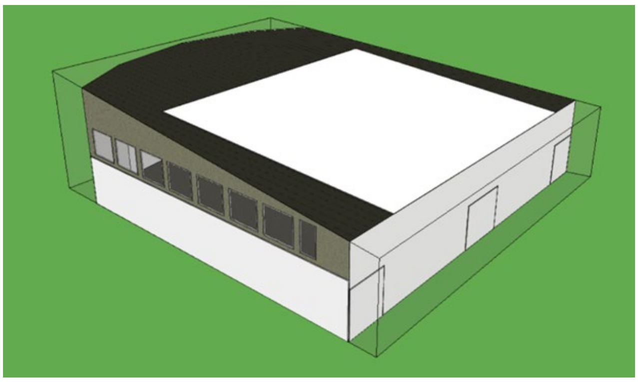


Figure 3. Model of the Amphitheater A

Figure 4. Google maps view on the zone

Figure 4 illustrates the orientation of the building and the amphitheater, which is also incorporated into the IDA ICE simulation software.

Another important aspect of the control algorithm for the model is the collection of setpoint for the ventilation and the limits for the regulating signals:

- Temperature:
  – Min Setpoint for heating controller = 20◦ C
  – Max Setpoint for cooling controller = 26◦ C
- Mech. supply air flow
  – Min Minimum flow at VAV. Recommended minimum airflow. = 3 $^{L}/_{sm^2}$
  – Max Maximum flow at VAV. Recommended maximum airflow. = 8 $^{L}/_{sm^2}$
- Mech. return air flow
  – Min Minimum flow at VAV. Recommended minimum airflow. = 3 $^{L}/_{sm^2}$
  – Max Maximum flow at VAV. Recommended maximum airflow. = 8 $^{L}/_{sm^2}$
- Level of carbondioxide
  – Min Level of CO_2 below which maximum VAV flow is kept. Only for VAV with CO_2 controlling. = 400 ppm (vol)
  – Max Level of CO_2 above which maximum VAV flow is kept. Only for VAV with CO_2 controlling. = 1100 ppm (vol)

Setpoints for the model were set accordingly to the calculations. The temperature setpoint refers to the value of the mean air temperature, which will be the parameter regulated during the simulations. The ventilation system is balanced, meaning that the supply and return airflows must be equal. For variable air volume (VAV) ventilation, the minimum airflow volume should be at least 30% of the maximum airflow to ensure that conditioned air effectively reaches the occupants. If the airflow is too slow, it could result in dead zones where fresh air does not circulate properly. The upper airflow limit is set to match the supply airflow used in the CAV ventilation system. The CO_2 level has a maximum limit of 1100 ppm, the threshold where people may start to feel drowsy, while the minimum is set at the ambient level of 400 ppm.

2.3 Scenarios

Occupancy changes are the most unpredictable parameter that must be observed and monitored to ensure that air temperature, indoor air quality, and overall occupant comfort are maintained. Different scenarios were selected to reflect real-life situations that may occur.

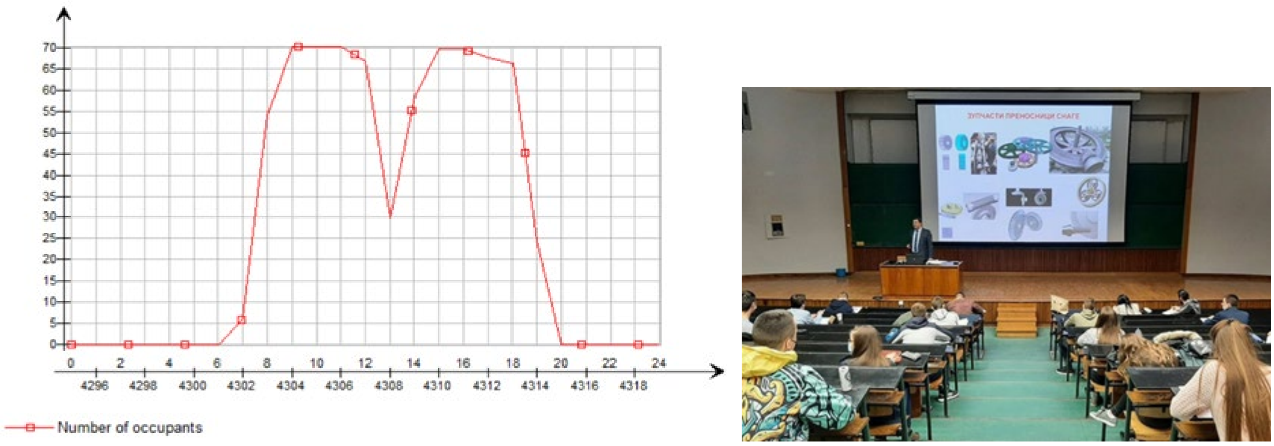
The reference scenario represents the validation of the model. The CAV system is designed for the maximum occupancy of 500 people and the airflow is calculated using the equation:

$$\dot{V} = \frac{Q_{max}}{c_p\, \rho\, \Delta t} = \frac{55600}{1010 * 1.2 * 9} = 5\ \frac{\mathrm{m}^3}{\mathrm{s}} \tag{1}$$

This airflow rate also serves as the upper limit for the VAV systems. Maximum occupancy is present in the zone from 08:00 to 19:00 on a warm summer day (June 28th was selected as a representative day, as it exhibits similar temperature variations to the summer project day).

The reference scenario is unlikely to happen, b but the following two scenarios represent real-life situations that will occur.

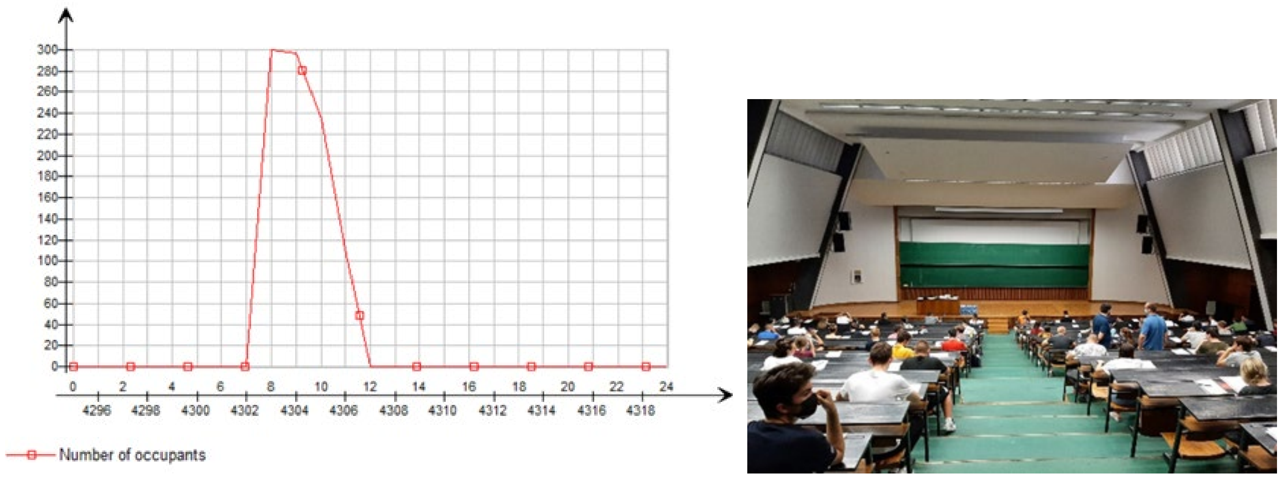
The first scenario models a typical day of lectures, starting on the hour from 08:00 to 19:00, with 15-minute breaks before each class and a longer break from 12:45 to 14:00. The schedule shown on the Figure 5. a) has smoothing applied, so it doesn’t have emphasized peaks that would occur because of the frequent breaks.



a) Schedule b) A lecture in the amphitheater

Figure 11. Occupancy during a lecture

The second scenario simulates students taking an exam. The occupancy trend is shown in Figure 6.



a) Schedule b) An exam in the amphitheater

Figure 6. Occupancy during an exam

Naturally, not all 300 students present at the start of the exam will stay for the entire duration; after 2 hours and 30 minutes about 50% remain, and the rest gradually leave in the following one and a half hours.

3. Results and discussion

The energy balance results for the reference scenario using the CAV model are presented in Figure 7. A constant ventilation flow of 5 $^{m^3}/_{s}$ (18000 $^{m^3}/_{h}$ or 8 $^{L}/_{sm^2}$) was set for the 625 m² floor area and the total volume of the zone around 4500 m3. The energy balance of the zone shows that the heat load around 17:00 is approximately 58 kW, while the calculated value is 54.6 kW (see Table 1.), resulting in a 6% error.

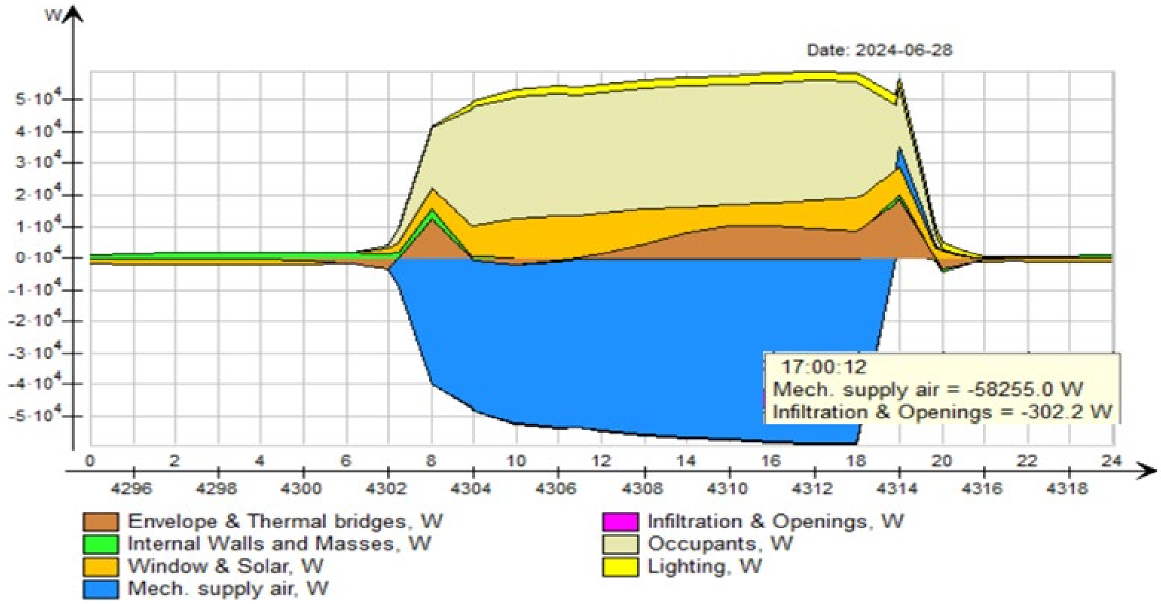


Figure 7. Validation of the model

Based on the desired temperature of 26°C, the mean air temperature remains (Figure 8.) close to this target but does not achieve a perfect match throughout the simulation. Slight fluctuations can be observed.

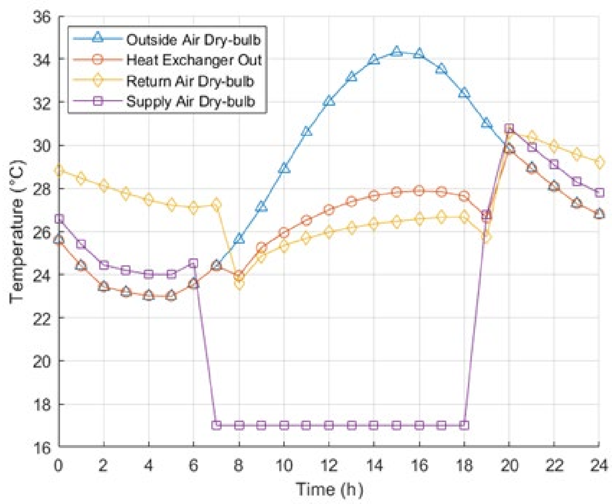
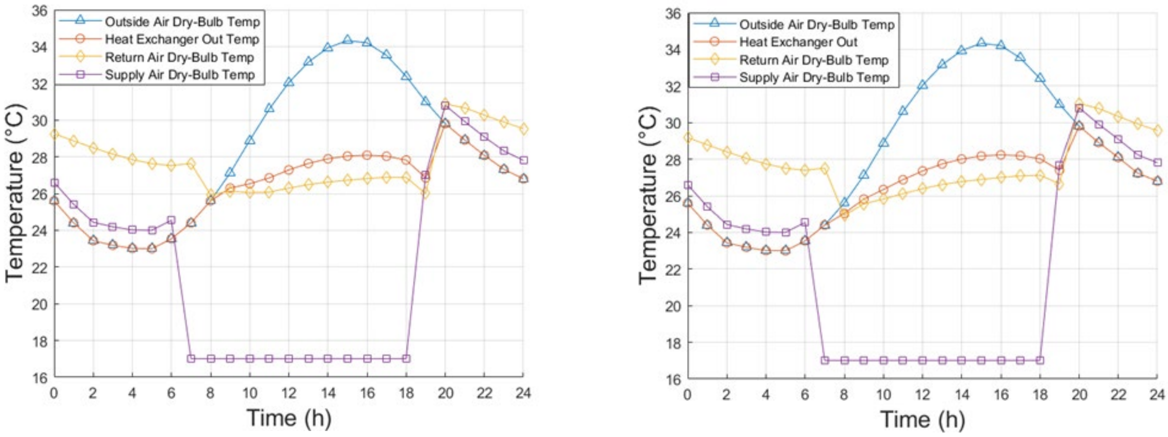


Figure 8. Air temperature for CAV system

A notable dip, or negative peak, in the return air temperature occurs when the ventilation system is activated one hour prior to the start of the occupancy schedule. This early activation helps precondition the space but also contributes to temporary deviations from the setpoint temperature, especially during the initial phase before occupants enter the zone. The constant rise in temperature is caused by the increase in outdoor temperature throughout the day. This is because the CAV system maintains a constant airflow, preventing it from adjusting the cooling rate as needed to compensate for the rising external heat. As a result, the system is unable to adequately control the temperature in the zone beyond that point.

The VAV with temperature control (Figure 9. a))clearly shows that the mean air temperature can be kept at a constant 26◦C as it represents the setpoint value, but not all the time.



a) Temperature control *b) CO2 control*

Figure 9. Air temperatures for VAV systems

The setpoint of 26°C is reached around 12.00h, but temperature regulation becomes ineffective afterward because the maximum airflow is reached, so nothing can help in lowering down the air temperature in the zone. In the interval before 12.00h the changing air flow keeps the air temperature at a setpoint value. For the VAV system with CO_2 control (Figure 9. b)), it operates similarly to a proportional (P) regulator, where the airflow to the zone is directly proportional to the CO_2 concentration. As the CO_2 level in the zone approaches a steady state, the airflow stabilizes and maintains a constant value, ensuring that indoor air quality is kept within acceptable limits while adjusting ventilation based on real-time occupancy and CO_2 levels (Figure 11.).

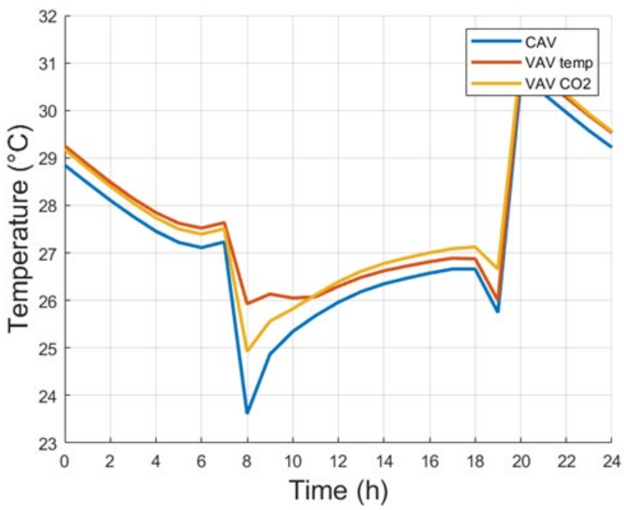


Figure 10.. Comparison of all mean air temperatures for ventilation systems

Comparison of all mean air temperatures for all three ventilation systems is given in the Figure 10. It can be noticed that there isn't very big difference in performance, especially after 12.00h, when the heat loads are bigger than the maximum calculated load in the Table 1.

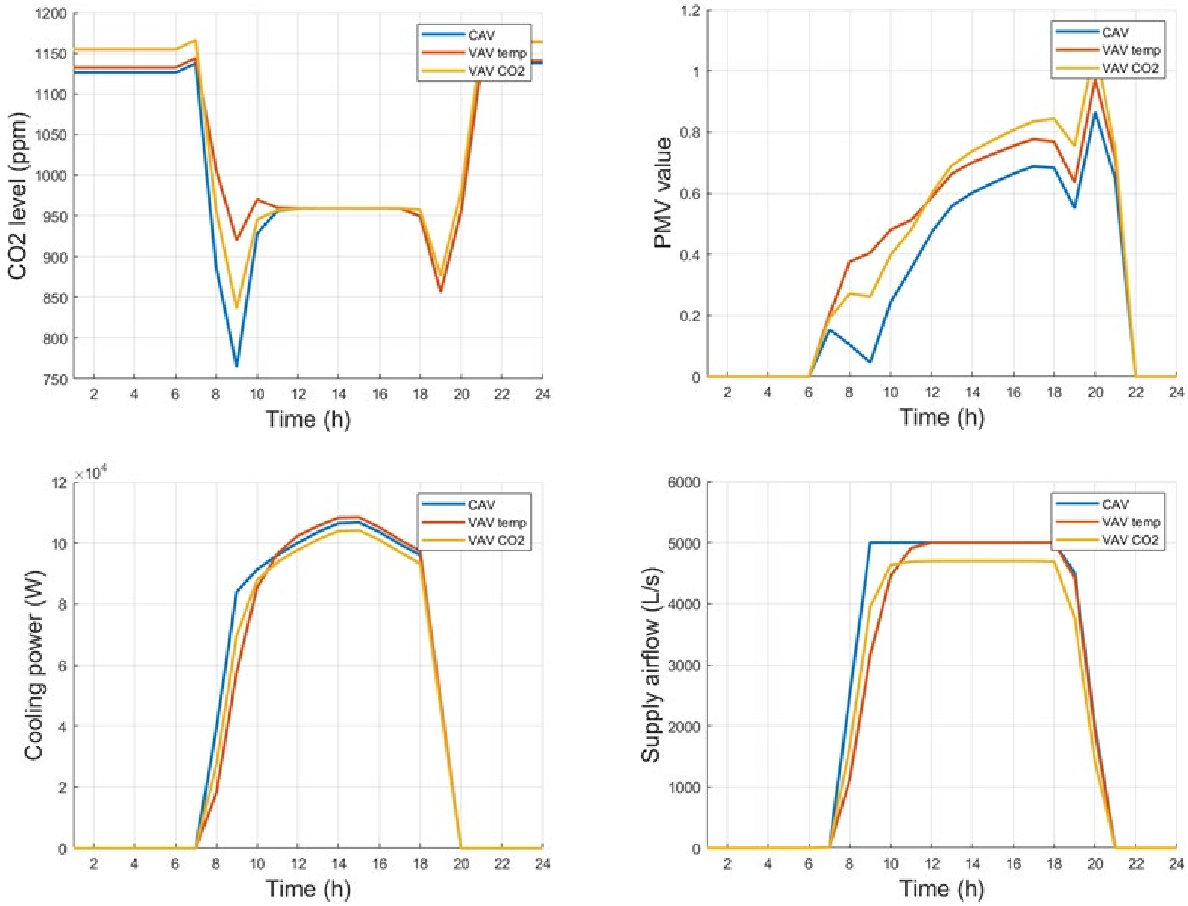


Figure 11. Comparison of additional characteristics for the reference scenario across all types of ventilation systems

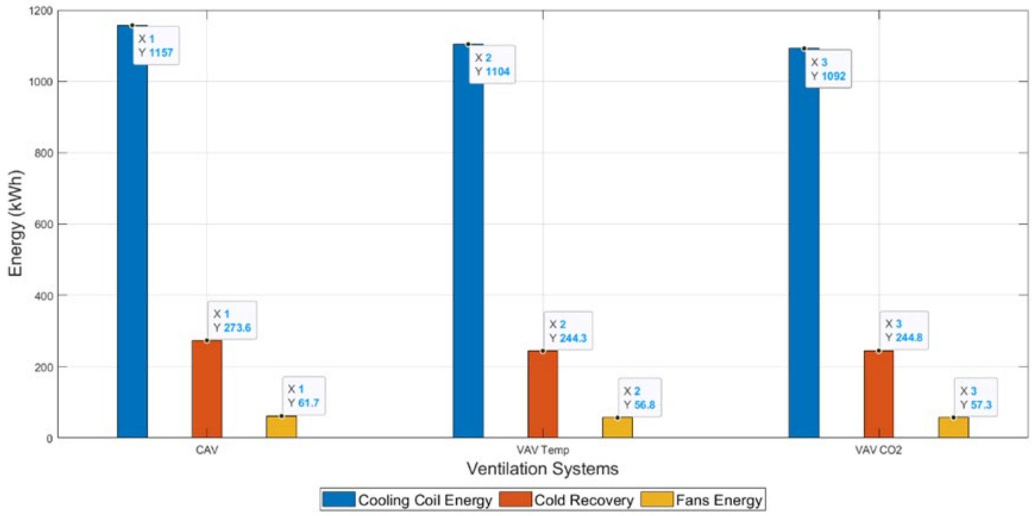


Figure 12. Energy usage for reference scenario

It can be observed in Figure 11. that all characteristics and indices are quite similar, owing to the predictable occupancy schedule and the ventilation system suitable for the reference model. All energy use values are illustrated in Figure 12, and there are no significant differences in energy use among the systems.

3.1 Lectures - scenario

As described in subsection 2.3, "Scenarios," the scenario for the all-day lectures is simulated. Figure 13. clearly illustrates significant differences among the three cases. The CAV system delivers excessive airflow to the zone, resulting in an air temperature around 23°C, which is undesirable, especially during the summer months. The PMV value diagram (Figure 14. b)) indicates that, while people in the room generally feel comfortable, some may feel slightly cooler, which is unwanted, especially in the summer months.

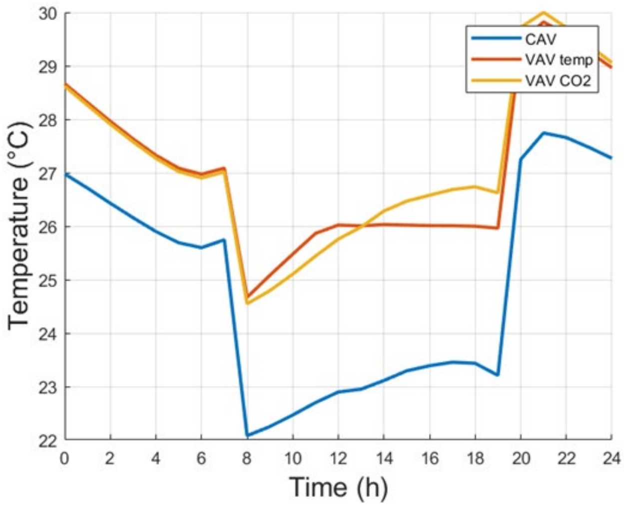
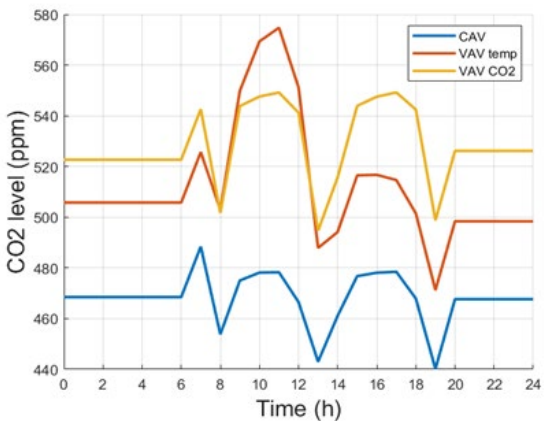
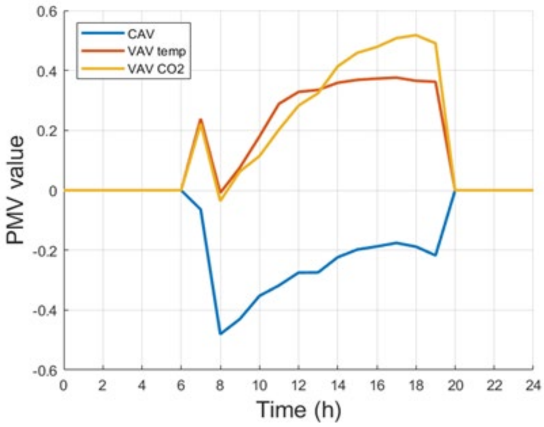


Figure 13. Comparison of mean air temperatures for lectures scenario

In contrast, the VAV system with temperature control effectively pre-cools the air and maintains it at a constant setpoint value. While the VAV system with CO_2 control performs better than the CAV, yet worse than previos VAV system, it in terms of managing air quality, it does not consistently achieve the desired temperature setpoint. Instead, it supplies air in accordance with the CO_2 levels, as depicted in Figure 14 a).



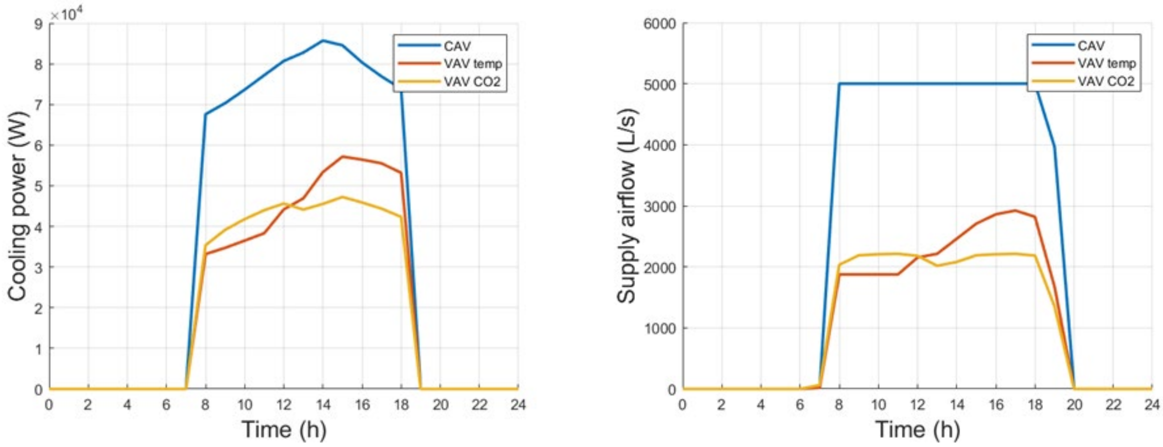
a) CO2 value



b) PMV value

Figure 14. Indices for the lectures scenario

The comparison in the energy usage is huge as shown in Figure 16. About 40% reduction in cooling coil energy is going to make a lot of saving, and the fans are working with 50% less energy. However, when examining the previous diagrams—especially those related to occupant comfort and indoor air quality—it becomes evident that the VAV systems outperform CAV. They deliver comparable results in maintaining comfort and air quality while using considerably less energy, highlighting the advantages of implementing VAV systems in such settings where the occupancy is variable, and even if it is unpredictable.



a) *Cooling power* b) *Supply airflow*

Figure 15. Air flow and cooling power for lectures scenario

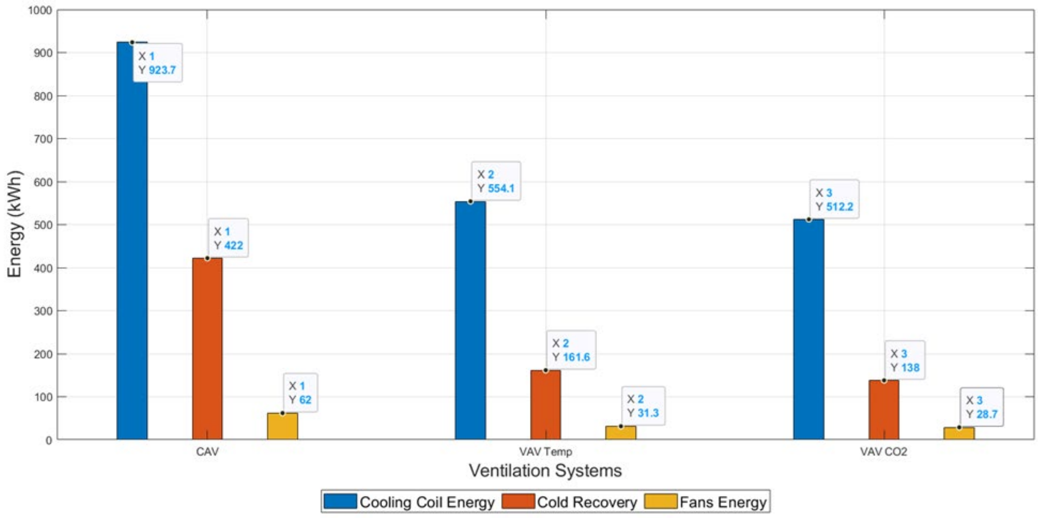


Figure 16. Energy usage for lectures scenario

3.2 Exam – scenario

In the case of shorter-lasting and variable occupancy such as when students are taking an exam, the results are the following:

In this scenario, similar to the previous one, the air temperature (Figure 17.) for both VAV systems hovers around the setpoint value of 26°C. The CO_2 generated by the occupants, along with the heat load they produce, has a comparable impact on the airflow supplied to the zone, which explains why both systems effectively maintain the temperature close to the desired level. The key difference lies in how each system achieves this: the VAV system with CO_2 control indirectly regulates the temperature by adjusting airflow based on CO_2 levels, while the VAV system with temperature control directly manages the temperature to keep it stable.

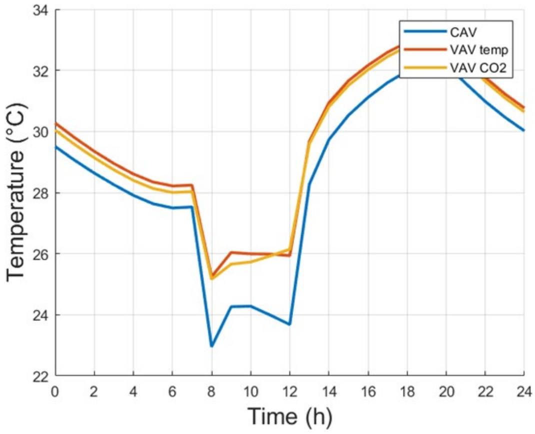
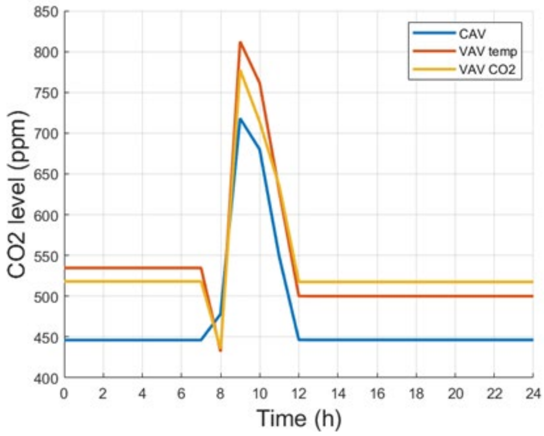
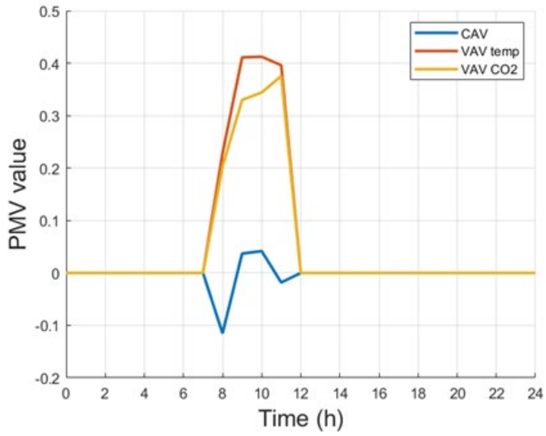


Figure 17. Comparison of mean air temperatures for exam scenario

Referring to Figure 18. b), the CAV model gives the impression of ideal comfort indices, while both VAV systems maintain values around +0.4, which is still well within acceptable comfort levels.



a) CO2 value



b) PMV value

Figure 18. Indices for the exam scenario

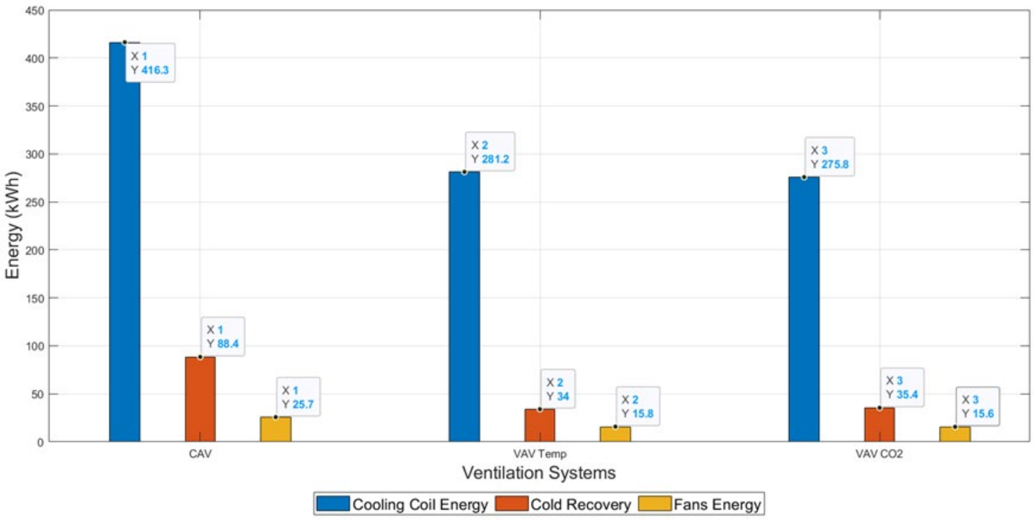


Figure 19. Energy usage for exam scenario

Although the CAV system produces better comfort, this comes at a significant energy cost. The cooling coil energy use increases by approximately 50%, and the energy demanded by the fans rises by about 65%, as shown in Figure 19. This highlights the trade-off between slightly improved comfort and much higher energy usage.

4. Conclusion

The aim of this study was to demonstrate the benefits of implementing a Variable Air Volume (VAV) ventilation system in large spaces like an amphitheater, where maintaining good indoor air quality is crucial for students. Optimal air quality can help them feel more alert and focused during lectures or when taking exams, while also minimizing costs and reducing the environmental impact by using less energy. This balance between comfort and efficiency highlights the importance of sustainable ventilation strategies in educational settings.

In the reference scenario, the absence of significant differences in energy use indicated that each ventilation system performed comparably under the specified conditions. This finding emphasized the importance of understanding how different systems could achieve similar performance levels, especially in environments with predictable usage patterns. Although this scenario was unlikely to occur in real life, it served to validate the reliability of the simulated model and demonstrated that Constant Air Volume (CAV) ventilation could also be valuable in managing predictable heat loads, but also when properly dimensioned for the specific scenario.

In the first scenario, which simulated professors delivering lectures throughout the day, high energy use occurred when using the Constant Air Volume (CAV) system, as it was dimensioned for the maximum occupancy of 500 people, while only a fraction of that capacity was present. The system's inability to adjust airflow to lower occupancy levels led to unnecessary energy usage, making it inefficient in such cases. The Variable Air Volume (VAV) system with temperature control delivered better results in terms of comfort compared to the VAV system with CO_2 control, although it consumed slightly more energy. The fluctuating occupancy levels caused CO_2 concentrations to vary, effectively simulating a real-life scenario. In this situation, the CAV system was not recommended due to its inefficiency. However, if the CAV system had to be used, implementing a manual ON-OFF control strategy could have helped save energy while still maintaining acceptable performance.

The conclusion for the exam scenario was straightforward: Variable Air Volume (VAV) systems were essential for achieving energy efficiency while delivering desirable results, such as high comfort levels and satisfactory indoor air quality. The outcomes of both VAV systems were quite similar, largely due to their shared working mechanisms for regulating air temperature when occupancy was the primary variable. However, in cases where other loads—such as equipment or lighting—contributed to heat without generating CO_2 (unlike humans), the two systems produced different results. In such situations, a VAV system that controlled both temperature and CO_2 would have been most suitable. The operating principle was that temperature was the primary parameter to be maintained at the setpoint, but if CO_2 levels exceeded predefined limits (with only the upper limit considered), the ventilation rates adjusted accordingly to ensure optimal conditions.

Acknowledgements

The results shown here are the result of research supported by the Ministry of Science, Technological Development and Innovation of the RS under the Agreement on financing the scientific research work of teaching staff at accredited higher education institutions in 2024, no. 451-03-65/2024-03/200105 of February 5, 2024.

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